AFWAL-TR-83-4125

HYDROLYTIC DEGRADATION OF KAPTON FILM

D. Robert Askins

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
300 College Park Avenue
Dayton, Ohio 45469

December 1983

Interim Technical Report for the Period: January 1983 - July 1983

Approved for public release; distribution unlimited

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Edward J. Morrisey

MR. EDWARD J. MORRISEY
Materials Engineering Branch
Systems Support Division
Materials Laboratory

Theodore J. Reinhart

MR. THEODORE J. REINHART, Chief
Materials Engineering Branch
Systems Support Division
Materials Laboratory

Warren P. Johnson

WARREN P. JOHNSON, Chief
Systems Support Division
Materials Laboratory

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization, please notify AFWAL/MLSE, W-PAFB, OH 45433 to help us maintain a current mailing list."

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-83-4125	2. GOVT ACCESSION NO. AD-A139016	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Hydrolytic Degradation of Kapton Film		5. TYPE OF REPORT & PERIOD COVERED Interim Technical Report January 1983-July 1983
		6. PERFORMING ORG. REPORT NUMBER UDR-TR-83-95
7. AUTHOR(s) D. Robert Askins		8. CONTRACT OR GRANT NUMBER(s) F33615-82-C-5039
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Dayton Research Institute 300 College Park Avenue Dayton, Ohio 45469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 24210318
11. CONTROLLING OFFICE NAME AND ADDRESS Materials Laboratory (AFWAL/MLSE) Air Force Wright Aeronautical Laboratories Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE December 1983
		13. NUMBER OF PAGES 59
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Kapton	kinetics	moisture	elevated temperature
film	tensile	ultraviolet	
degradation	strength	polyimide	
hydrolysis	elongation	humidity	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An investigation of the hydrolytic degradation of Kapton polyimide film has been conducted. Tensile properties were measured on (a) unaged material, (b) material which had been immersed in water at temperatures from 50-100°C for up to 5,000 hours, (c) material which had been stressed to 5,000 psi while being exposed to 95-100% relative humidity at 75° and 85°C, and (d) material which had been repetitively cycled through a combination of ultraviolet radiation and condensing humidity at 50-60°C. The property degradation as a function of time

(Continued)

DD FORM 1 JAN 73 1473

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (Concluded)

was found to be best represented by an exponential decay curve for all exposure conditions. The immersion time required for the film to lose a prescribed percentage of its initial tensile properties was determined for each aging temperature, and these "lifetimes" were correlated with temperature using the Arrhenius relationship. Over the temperature range examined, excellent linearity was obtained. Following the same criteria as with the immersion specimen, "lifetimes" were determined for the stressed humidity exposures and ultraviolet-humidity cyclic exposures. Both of these exposure environments significantly accelerated the rate of degradation over that observed in the unstressed water immersions at equivalent temperatures.

FOREWORD

This report covers work performed during the period from January 1983 to July 1983 under Air Force Contract F33615-82-C-5039, Project 7381. The work was administered under the direction of the Systems Support Division of the Air Force Materials Laboratory, Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Mr. Ed Morrisey (AFWAL/MLSE) was the Program Project Engineer.

The principal investigator on this program was D. Robert Askins. The major portion of the laboratory work was conducted by Messrs. James McKiernan (program scheduling, data compilation and collation, water immersion agings, and QUV-humidity exposures), Don Byrge (mechanical testing), and Dan Miller and Bill Price (stressed humidity agings).

This report was submitted by the author in September 1983. The contractor's report number is UDR-TR-83-95.

TABLE OF CONTENTS

SECTION		PAGE
1	INTRODUCTION	1
2	MATERIALS AND TEST PROCEDURES	3
	2.1 MATERIALS	3
	2.2 TENSILE TEST METHODS	3
	2.3 EXPERIMENTAL OUTLINE	5
	2.4 THEORETICAL BASIS FOR TREATMENT OF DATA	6
3	BASELINE CONTROL TESTS	12
4	UNSTRESSED WATER IMMERSION EXPOSURES	14
	4.1 EXPOSURE AND TEST PROCEDURE	14
	4.2 DISCUSSION OF RESULTS	14
5	STRESSED HUMIDITY EXPOSURES	22
	5.1 EXPOSURE AND TEST PROCEDURE	22
	5.2 DISCUSSION OF RESULTS	22
6	UNSTRESSED HUMIDITY-ULTRAVIOLET EXPOSURES	29
	6.1 EXPOSURE AND TEST PROCEDURE	29
	6.2 DISCUSSION OF THE RESULTS	29
7	CONCLUSIONS	37
8	REFERENCES	39
	APPENDIX - COMPLETE TEST DATA	40

Preceding Page Blank

LIST OF ILLUSTRATIONS

FIGURE		PAGE
1	Kapton Film Tensile Specimen in Instron Grips	4
2	Kapton-Fiberglass Spool for Unstressed Water Immersion Exposures	15
3	Effect of Unstressed Environmental Aging on Retention of Tensile Strength of Kapton Film	17
4	Effect of Unstressed Environmental Aging on Retention of Tensile Elongation of Kapton Film	18
5	Effect of Temperature Upon Lifetime (20% Decrease in Tensile Strength) of Kapton Film	20
6	Effect of Temperature Upon Lifetime (50% Decrease in Tensile Elongation) of Kapton Film	21
7	Method of Gripping and Loading Kapton Film During Stressed Humidity Exposures	23
8	Effect of Stressed vs. Unstressed Environmental Aging on Tensile Strength Retention of Kapton Film	24
9	Effect of Stressed vs. Unstressed Environmental Aging on Retention of Tensile Elongation of Kapton Film	25
10	Effect of Temperature Upon Lifetime (20% Decrease in Tensile Strength) of Kapton Film	27
11	Effect of Temperature Upon Lifetime (50% Decrease in Tensile Elongation) of Kapton Film	28
12	Typical 24 Hour QUV Cabinet Temperature Record	30
13	QUV Accelerated Weathering Test Cabinet and Specimen Arrangement	31
14	Effect of Unstressed Environmental Aging @ 60°C in Water vs. Cyclic Wet/Dry QUV Exposure @ 55-60°C on Retention of Tensile Strength of Kapton Film	32
15	Effect of Unstressed Environmental Aging @ 60°C in Water vs. Cyclic Wet/Dry QUV Exposure @ 55-60°C on Retention of Tensile Elongation of Kapton Film	33

LIST OF ILLUSTRATIONS (Concluded)

FIGURE		PAGE
16	Effect of Temperature Upon Lifetime (20% Decrease in Tensile Strength) of Kapton Film	35
17	Effect of Temperature Upon Lifetime (50% Decrease in Tensile Elongation) of Kapton Film	36

LIST OF TABLES

TABLE		PAGE
1	Tensile Properties of Fresh, Unaged Kapton Film	13
2	Effect of Exposure to Various Environments on Room Temperature Tensile Properties of Kapton Film	16
A.1	Control Properties of Unaged Kapton Film	41
A.2	Residual Properties of Kapton Film After Water Immersion at 100°C	42
A.3	Residual Properties of Kapton Film After Water Immersion at 85°C	43
A.4	Residual Properties of Kapton Film After Water Immersion at 75°C	44
A.5	Residual Properties of Kapton Film After Water Immersion at 70°C	45
A.6	Residual Properties of Kapton Film After Water Immersion at 60°C	46
A.7	Residual Properties of Kapton Film After Water Immersion at 50°C	47
A.8	Residual Properties of Kapton Film After Unstressed Exposure to Ultraviolet and Humidity in QUV Cabinet	48
A.9	Residual Properties of Kapton Film After Stressed-Humidity Exposures at 85°C	49
A.10	Residual Properties of Kapton Film After Stressed-Humidity Exposures at 75°C	50
A.11	Properties of Unaged Kapton Film as Determined by DuPont	51

SECTION 1
INTRODUCTION

Kapton[1] polyimide film is in wide use as a high temperature electrical wire insulation in many military aircraft. Concern has been raised during recent years that this type of insulation is susceptible to hydrolytic degradation, leading to cracks in the insulation which can give rise to electrical malfunctions. As a result of this concern, a number of investigations have been conducted. Some of these studies have dealt with insulated wire and have relied on changed in resistivity or electrical breakdown as a measure of degradation. Other investigations have been concerned with film behavior, relying on changes in film tensile strength or elongation to measure degradation.

Three previous studies of the hydrolysis of Kapton film[2-4] developed considerably different kinetic degradation rate parameters. While both investigations reported that plots of retained tensile properties as a function of exposure time to water exhibited asymptotes after appropriate exposure periods below which the properties did not fall, they disagreed on both the level of the asymptote and the rate at which it was approached. The Grumman results indicated a considerably lower initial tensile elongation, a considerably lower asymptotic elongation level, and a considerably more rapid loss of exposure time.

One purpose of this investigation was to generate mechanical property data to aid the Air Force in assessing the relative seriousness of the wire insulation problem. Secondly, since most of the laboratory data regarding Kapton film hydrolysis (and accompanying mechanical property degradation) was obtained by exposing the film to boiling water (100°C), it was desired to determine whether the hydrolytic degradation at lower temperatures could be represented by the standard Arrhenius type relationship, and therefore used to estimate degradation times at other temperatures.

SECTION 2
MATERIALS AND TEST PROCEDURES

2.1 MATERIALS

All of the material tested during this investigation was supplied by DuPont. It consisted of two, one-half inch wide slit rolls of 100H Kapton polyimide film. These two rolls represent adjacent slit lanes from the same mill roll (No. 00792). The film was 0.001 inch thick. The tensile behavior of this film is very sensitive to edge defects such as nicks or tears.

2.2 TENSILE TEST METHODS

All of the test data presented in this report represents the results of room temperature tensile tests on one-half inch wide Kapton film. The tests were conducted either on as-received unaged film or on film aged at one of the various exposure conditions and tested for residual strength.

Each specimen tested, both baseline and after exposure, was five inches long with a two-inch gage section between grips. Specimens were gripped in an Instron test machine with smooth rubber faced pneumatic grips and tested at a crosshead speed of two inches/minute. Figure 1 illustrates a tensile specimen in the Instron grips. Both load and crosshead travel were recorded. Tensile strength was calculated on the basis of constant specimen cross-sectional dimensions of 0.500 inch wide by 0.001 inch thick. Elongation, derived from crosshead travel, was based on an initial specimen gage length of two inches.

All specimens were visually inspected for edge defects, and while very few edge defects were apparent, only specimens with defect free edges were used.

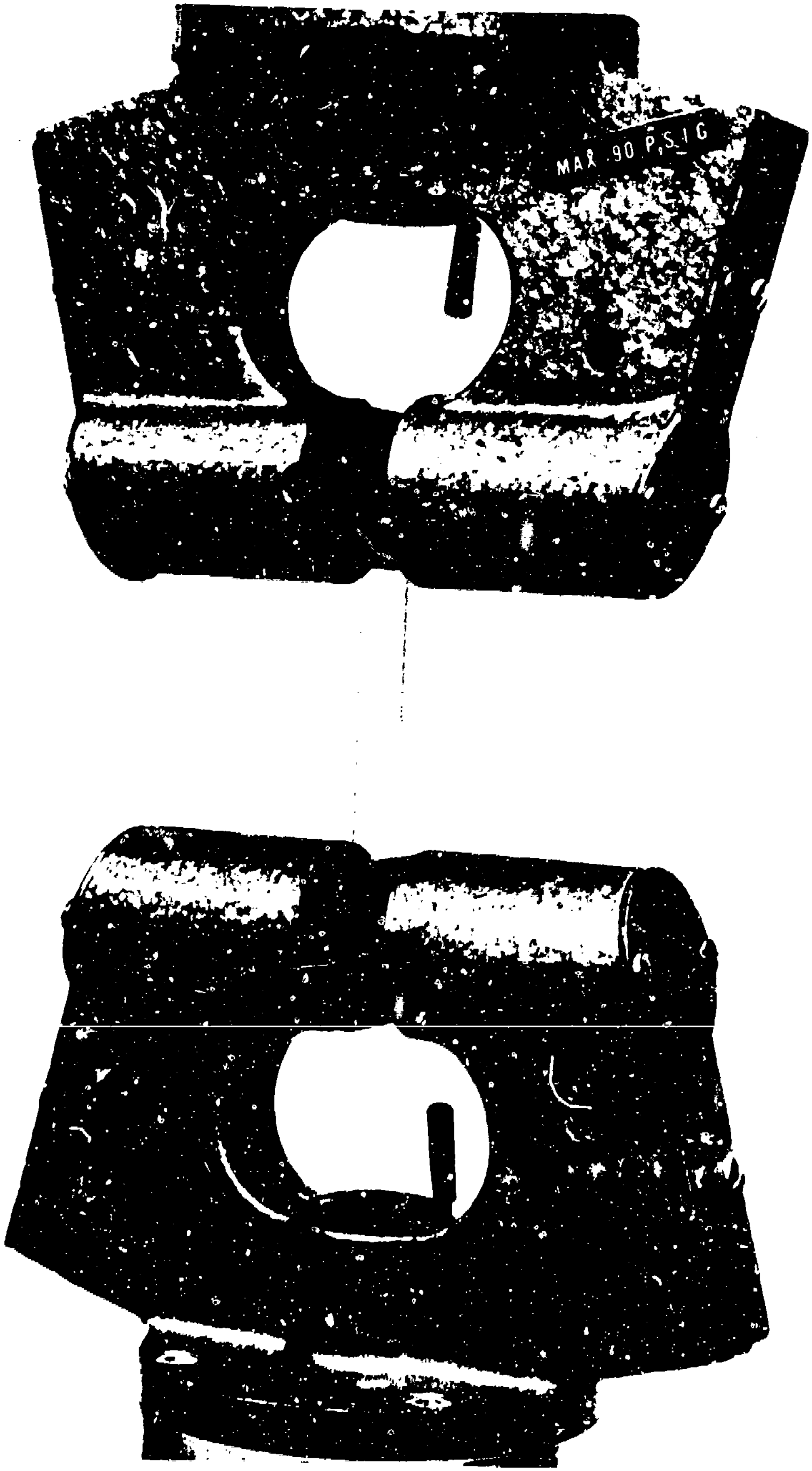


Figure 1. Kapton Film Tensile Specimen in Instron Grips.

In each phase of the program, and for each exposure time within each phase, a sufficient number of replicate tests were conducted to ensure (with two exceptions noted below) that twenty good individual data points could be included in an average value for that particular set of test parameters. A good data point was defined as one deriving from a specimen which, when tested in tension, did not fail at the edge of the grip at an unusually low load and elongation. Thus, a good data point would result from any specimen not failing at a grip edge or from a specimen which did fail at a grip edge but at a load or elongation equal to or above the average for all the other replicate samples within the set.

Generally, the entire sample set for any one set of conditions consisted of 24-46 specimens. The first twenty "good" test results were used in the average values presented in the following tables. The appendix presents tabulations of the complete test data.

There were two exceptions to the above statement that at least twenty "good" data points are incorporated into each average value presented in the subsequent sections. These exceptions were for the stressed agings described in Section 5.2. In each case, over 40 specimens were under test at the beginning of the stressed exposure period, but so many failed during exposure that fewer than 20 survived for residual strength testing.

2.3 EXPERIMENTAL OUTLINE

The program was subdivided to form different work phases. These were as follows:

(a) Baseline Control Tests on Unaged Film,
(b) Unstressed Water Immersion Exposures,
(c) Stressed Humidity Exposures, and
(d) Unstressed Humidity-Ultraviolet Exposures.

The baseline test phase involved the generation of tensile data on unaged Kapton film, while the other three involved various environmental exposure conditions followed by residual film tensile tests for comparison to the baseline data. Each of these are described in more detail in Sections 3 and 4.

2.4 THEORETICAL BASIS FOR TREATMENT OF DATA

Hydrolytic degradation has been investigated for a variety of different types of polymeric materials and the data analyzed kinetically. Welch and Lofgreen[5] examined the humidity aging of elastomeric potting compounds and determined that the reaction (reversion) rate could be satisfactorily represented as a first order reaction with respect to water vapor concentration, and that the use of the Arrhenius relationship permitted prediction of service life (arbitrarily defined) for different temperatures. Berner[6] studied a polyester mat and a polyester polyurethane foam. He also found that the reaction rate was a first order function of water vapor concentration and that service life could be predicted from accelerated laboratory tests using the Arrhenius relationship.

The studies cited above were conducted by exposing the polymeric materials to a matrix of environmental conditions consisting of various temperatures and relative humidity levels. In analyzing the experimental results, the assumption was made that since the polymer concentration was the same in all of the different exposure conditions, it could be treated as a constant in the rate equation. Further, the assumption was made that the reaction rate was constant throughout the period of hydrolysis. While this assumption is reasonable for short periods, its validity over long time periods is questionable.

In this investigation, the controlled test parameter was exposure temperature. In the water immersion tests, the water concentration external to the specimens was constant. The water concentration level within the film may depend on immersion temperature and is probably higher for the higher immersion temperatures than for the lower temperatures.

Germeraad and Cornelius[4] demonstrated the presence of chemically reactive sites in Kapton film which were susceptible to hydrolytic attack and suggested that they were the result of incomplete polyimide cyclization or the presence of small amounts of isoimide. Thus, a variety of different types of chain scission sites are present in Kapton film, each in its own particular concentration. Since we have no idea which type of site, if any, predominates, nor are the particular kinetics of hydrolysis of the different types of reactive sites known, the overall hydrolytic degradation rate is most readily considered as some sort of average overall reaction.

The hydrolysis process is believed to consist of a period of diffusion of water into the one mil thick film until an equilibrium absorbed moisture content is achieved. During this preequilibrium period, the hydrolysis reaction rate is probably dependent upon both the water concentration and the concentration of available chain scission sites within the Kapton film, as well as the particular kinetics for each type of available chain scission site. Once equilibrium water diffusion into the film is achieved, the water concentration within the film becomes constant, although this constant level may be dependent upon temperature. In-house studies[7] of liquid absorption by polyimide film indicate that the time required to reach equilibrium diffusion is negligible in comparison to the length of time over which exposures were conducted here. Hence, the hydrolysis reaction rate becomes essentially a function only of the concentration of available chain scission sites.

Following this reasoning and utilizing some sort of average overall reaction as representative of the bulk polymer behavior, one best represents the reaction rate mathematically as:

$$\bar{r}_s = -\frac{d\bar{c}_{ss}}{dt} = k_1 \, \bar{c}_{ss}^{\,n} \qquad (1)$$

where:

$\bar{r}_s$ = average rate at which chain scission sites are undergoing hydrolytic scission (scissions/hr)

$\bar{c}_{ss}$ = average concentration of various types of chain scission sites (sites/liter)

k_1 = average chain scission rate constant, dependent on temperature

n = average order of the reaction with respect to the various types of chain scission sites.

Wallach[8] has presented data indicating that a nearly linear relationship exists between tensile strength and elongation and molecular weight of polyimide over the range of strength and elongation changes of concern in this program. Thus, as chain scission progresses and average molecular weight decreases, tensile properties decrease in concert with the reaction rate, and it can be reasoned that the rate of change of the film tensile properties can be described by an equation of the same form as (1), i.e.,

$$-\frac{d\,(UTS)}{dt} = k_2 \, (UTS)^n \qquad (2)$$

where:

UTS = ultimate tensile strength

k_2 = rate constant dependent on temperature [as in equation (1)]

The order of reaction is determined most easily by integrating equation (2) for various values of n, fitting the data to the various types of curves which result and determining which fits best. A zero order reaction would yield a straight line. A first order reaction yields an exponential decay curve. A second order reaction produces a curve with the same general shape as the exponential decay curve. There is no basis, however, for the hydrolysis reaction to be higher order since the chain scissions involve the breaking of a single bond each. Further, the previous work cited on hydrolytic degradation of various types of polymers found that the reactions were always first order. The experimental data obtained in this investigation was fitted to the equations which result for n = 0, 1, and 2, and it was found that the exponential decay form for n = 1 did indeed provide the best fit. Thus, integration of equation (2) for n = 1 yields

$$\int \frac{d(UTS)}{UTS} = \int k_2 dt$$

$$\ln(UTS) = k_2 t + c$$

where:

c = constant of integration.

In exponential form,

$$UTS = \frac{1}{c} e^{-k_2 t} = c' e^{-k_2 t} \qquad (3)$$

where:

c′ = UTS when t = 0.

Thus, all of the residual tensile strength and elongation data obtained for the various exposure conditions during this program have been fitted to exponential decay curves. These curves are plotted along with the experimental data in the subsequent figures.

A "lifetime" for each exposure condition was defined as that time at which the residual tensile strength and elongation fell below 80% and 50%, respectively, of the original baseline values. These two lifetimes occurred at about, but not exactly at, the same aging time. These lifetimes were correlated with temperature using the Arrhenius relationship. Thus, from equation (3):

$$UTS^* = UTS_o \, e^{-k_2 t^*}$$

$$\frac{UTS^*}{UTS_o} = e^{-k_2 t^*}$$

where:

t^* = aging time required for residual tensile strength or elongation to fall to 80% or 50%, respectively, of initial value.

UTS_o = original ultimate tensile strength at $t = 0$

UTS^* = ultimate tensile strength when $t = t^*$

for $\frac{UTS^*}{UTS_o} = 0.8$ (definition of lifetime)

$e^{-k_2 t} = 0.8$, or in logarithmic form

$$-k_2 t^* = \ln 0.8 = -0.22314 \qquad (4)$$

where * indicates values when lifetime is reached, as: $UTS^* = 0.8\ UTS_o$, t^* = time for UTS to decay to UTS^*.

From the Arrhenius relationship

$$k_2 = Ae^{-E_a/RT} \qquad (5)$$

where:

A = frequency factor

E_a = activation energy

R = gas constant

T = temperature (absolute).

Combining equations (4) and (5),

$$-Ae^{-E_a/RT} t^* = -0.22314 \qquad (6)$$

$$t^* = \left(\frac{0.22314}{A}\right) e^{E_a/RT}$$

Logarithmically,

$$\log t^* = \log \left(\frac{0.22314}{A}\right) + \frac{E_a}{2.3\ RT} \qquad (7)$$

For the water immersion tests the log of the lifetime was plotted against the reciprocal temperature, and excellent linearity was obtained. These plots are presented and discussed in Sections 4-6.

SECTION 3
BASELINE CONTROL TESTS

Baseline tensile tests were conducted on each of the two rolls of Kapton film supplied by DuPont. Although tensile tests were conducted on both rolls of film received from DuPont, since all specimens used throughout the program were taken from the roll designated "C", the tensile properties for this roll were used as the baseline reference values for all residual property tests.

Table 1 presents the as-received tensile properties of each roll of Kapton film along with data obtained and supplied by DuPont for samples taken from the same mill roll but from adjacent slit lanes.

It is apparent that there is excellent agreement between UDRI and DuPont measurements of tensile strength, with all six values in Table 1 falling within 5% of the overall average of 34,200 psi (236 MPa). Tensile elongation data on the other hand exhibits some inexplicable disparities. The UDRI results are markedly lower than the DuPont values. The overall DuPont average elongation of 67.9% is about 25% higher than the overall UDRI average value of 53.6%. While the reason for this discrepancy is uncertain, it is probably due to a difference in procedure or interpretation. Since all of our results will be referenced to the baseline values as a percent-of-original, and the same procedures and methods of interpretation will be common to all data, it was not felt that the exact reason for the UDRI-DuPont elongation differences was worth pursuing.

TABLE 1

TENSILE PROPERTIES OF FRESH, UNAGED KAPTON FILM

Data Source	Tensile Strength				Tensile Elongation	
	Average (psi)	Average (MPa)	Standard Dev. (psi)	Standard Dev. (MPa)	Average (%)	Standard Dev. (%)
DuPont, roll "A", location 1	34,200	236	2,000	14	66.7	10.2
DuPont, roll "A", location 2	33,600	232	1,300	9	69.5	7.8
DuPont, roll "A", location 3	35,600	245	1,500	10	73.7	8.0
DuPont, roll "B"[1]	34,800	240	2,600	18	61.8	11.4
UDRI, roll "C"[2,3]	34,500	238	2,000	14	54.2	9.0
UDRI, roll "D"	32,600	225	2,600	18	52.9	11.8

[1]Values represent averages of ten samples each.

[2]Values represent averages of twenty samples each.

[3]Values for this roll are used as baseline reference values for percent retention values reported in Sections 4 through 6.

SECTION 4

UNSTRESSED WATER IMMERSION EXPOSURES

4.1 EXPOSURE AND TEST PROCEDURE

Unstressed water immersion tests were conducted at six different temperatures ranging from 50°C to 100°C. Long, continuous strips of Kapton film were taken from roll "C" and loosely wound, along with a continuous strip of fiberglass fabric, into a spool. The glass fabric served as a separator strip to ensure that water penetrated between each wrap of the film. This film-fiberglass spool is illustrated in Figure 2. This spool was placed in a beaker and covered with deionized water. The beaker was covered and placed in a circulating air oven at the desired exposure temperature. Oven temperature was monitored daily by multiple indicators to ensure proper control.

After prescribed aging periods, the beaker was removed from the oven, and residual tensile tests were conducted. Individual specimens were cut from the film spool with scissors and tested immediately. Between tests, the film spool was returned to the water filled beaker at room temperature to prevent dryout.

4.2 DISCUSSION OF RESULTS

Table 2 indicates the time-temperature test matrix followed for all of the various types of exposures discussed in Section 3 through 4 and also presents the results obtained. Figures 3 and 4 present the plots of residual strength and elongation as functions of immersion time at the various exposure temperatures. As discussed in Section 2.4, least square fits of the data to exponential decay curves are also drawn in and the lifetime identified for each temperature.

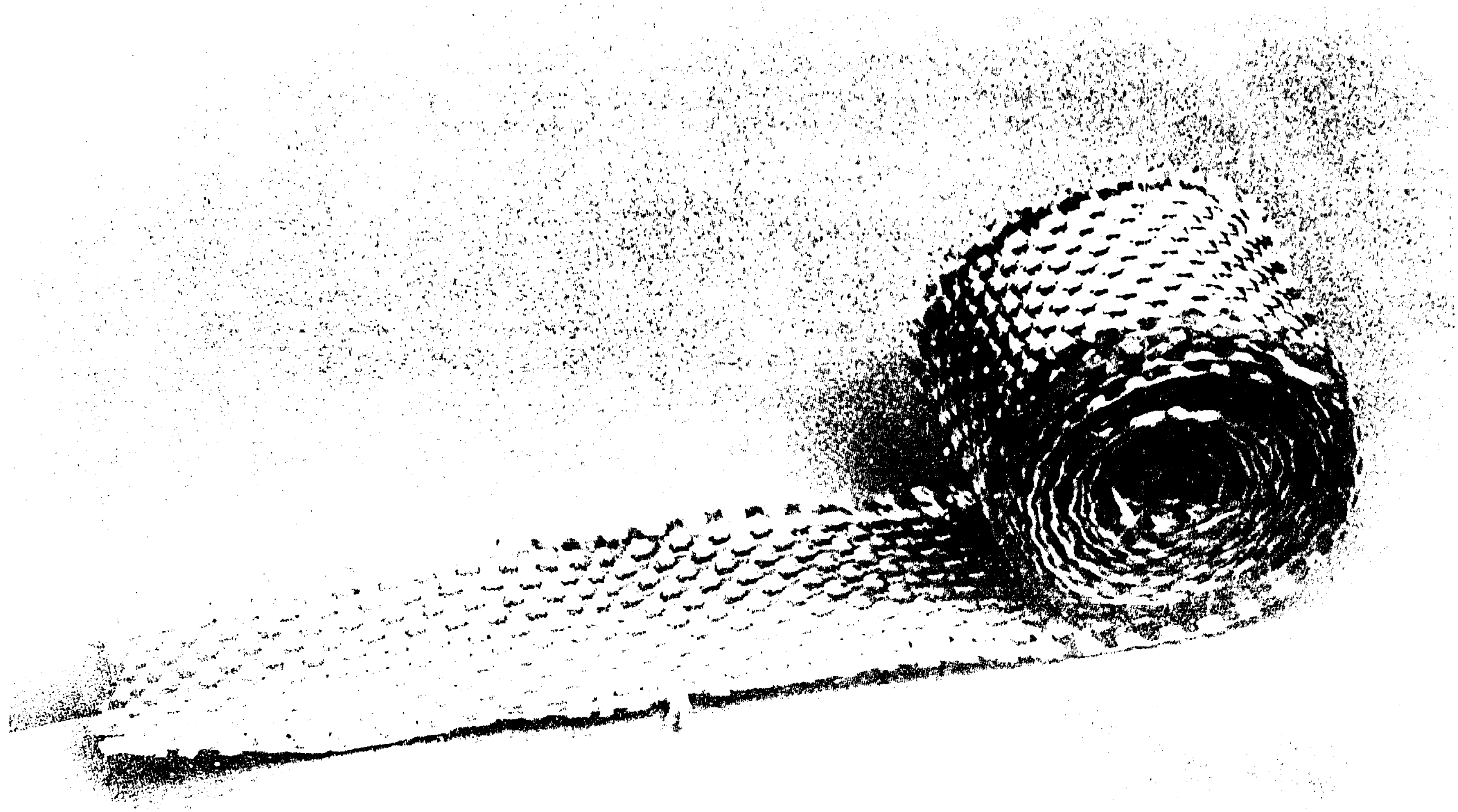


Figure 2. Kapton-Fiberglass Spool for Unstressed Water Immersion Exposures.

TABLE 2

EFFECT OF EXPOSURE TO VARIOUS ENVIRONMENTS ON ROOM TEMPERATURE TENSILE PROPERTIES OF KAPTON FILM

Exposure Condition	Exposure Temperature (°C) (°F)	Exposure Time (hrs)	Tensile Strength Average (ksi) (MPa)	Tensile Strength Std. Dev. (ksi) (MPa)	Tensile Strength % of Baseline	Ultimate Elongation Average (%)	Ultimate Elongation Std. Dev. (%)	Ultimate Elongation % of Baseline
No Exposure - Baseline	N.A.	N.A.	34.5 (238)	2.0 (14)	100	54.2	9.0	100
Unstressed Water Immersions	100 (212)	24	31.6 (218)	1.9 (13)	92	43.6	6.8	80
		112	28.0 (193)	1.6 (11)	81	33.0	7.0	61
		184	28.2 (194)	1.2 (8)	82	27.9	4.1	51
		376	26.5 (183)	1.3 (9)	77	24.7	4.3	46
	85 (185)	200	29.8 (205)	1.0 (7)	86	40.5	4.8	75
		600	26.5 (183)	0.9 (6)	77	26.2	3.5	48
	75 (167)	300	30.6 (211)	1.5 (10)	89	42.0	7.8	77
		600	29.5 (203)	1.3 (9)	86	37.8	6.1	70
		1000	27.8 (192)	0.9 (6)	81	30.3	4.2	56
	70 (158)	500	31.0 (214)	2.0 (14)	90	45.9	10.2	85
		1000	28.7 (198)	1.7 (12)	83	37.7	7.6	70
		1500	27.6 (190)	1.1 (8)	80	29.9	5.3	55
	60 (140)	750	29.4 (206)	1.4 (10)	87	41.9	6.8	77
		1500	28.5 (196)	1.5 (10)	83	32.8	7.1	61
		2250	27.7 (191)	1.2 (8)	80	29.9	5.6	55
		3000	26.7 (184)	1.2 (8)	77	27.1	5.0	50
		4000	26.7 (181)	2.3 (10)	77	21.6	5.7	40
	50 (122)	1000	30.6 (211)	2.0 (14)	89	45.2	8.7	83
		2000	30.3 (209)	1.5 (10)	88	42.1	7.7	78
		3550	28.9 (199)	1.6 (11)	84	36.9	7.2	68
		5000	26.6 (183)	1.2 (8)	77	25.4	4.8	47
Stressed Humidity Exposures, 5000 psi (34.5 MPa), 95-100% R.H.	85 (185)	200	28.7 (198)	2.6 (18)	83	31.0	8.1	57
		400	27.0 (186)	1.4 (10)	78	20.9	5.1	39
	75 (167)	300	29.6 (204)	1.1 (8)	86	32.9	7.0	69
		600	27.6 (190)	3.7 (25)	80	26.5	8.7	49
Unstressed Humidity Ultraviolet Exposure (see description in text)	55-60 (131-140)	200	32.1 (221)	1.4 (10)	93	48.6	6.6	90
		500	28.4 (196)	1.5 (10)	82	33.0	8.5	61
		1000	23.5 (162)	0.8 (6)	68	18.6	2.0	34

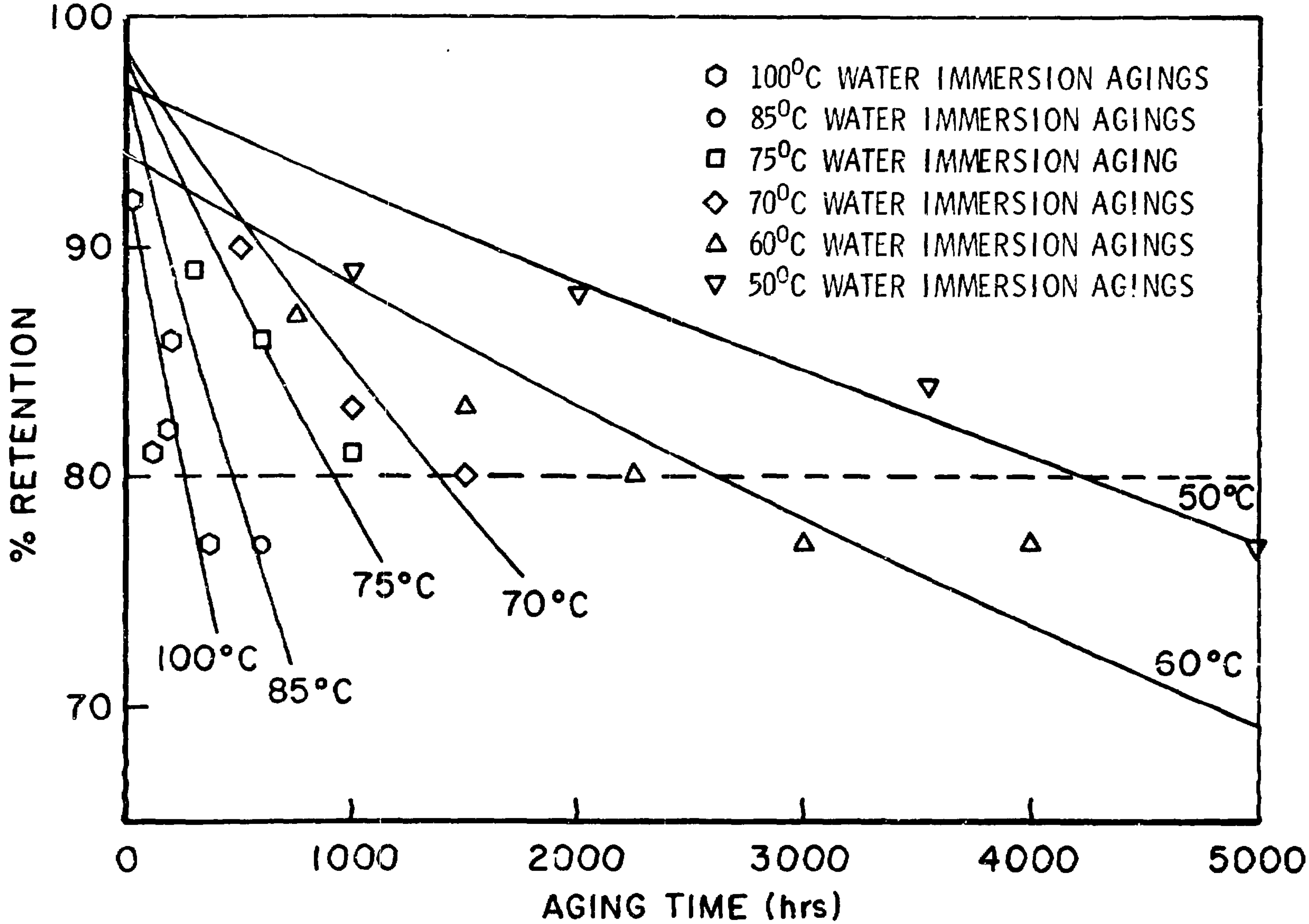


Figure 3. Effect of Unstressed Environmental Aging on Retention of Tensile Strength of Kapton Film.

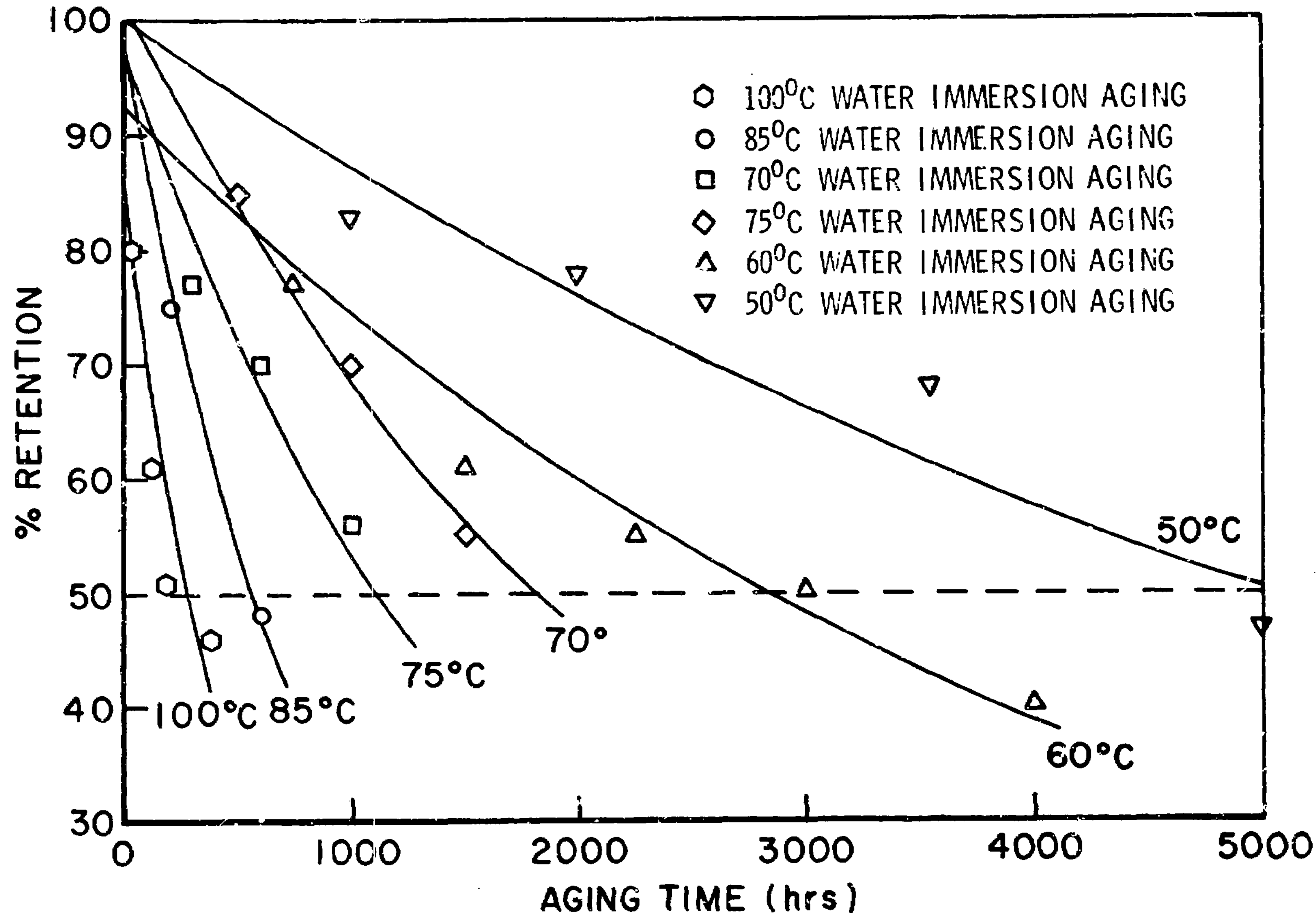


Figure 4. Effect of Unstressed Environmental Aging on Retention of Tensile Elongation of Kapton Film.

The effect of temperature upon the hydrolytic degradation of Kapton film is illustrated in Figures 5 and 6, where the Arrhenius relationship between lifetime (as defined here) and temperature is plotted. Figures 5 and 6 include data from references 2 and 3. It is apparent from the excellent linearity of the data that the Arrhenius relationship well represents the hydrolysis reaction of Kapton film over the temperature range of 50-100°C, and could probably be used to estimate lifetime at temperatures somewhat lower than these limits with reasonable confidence.

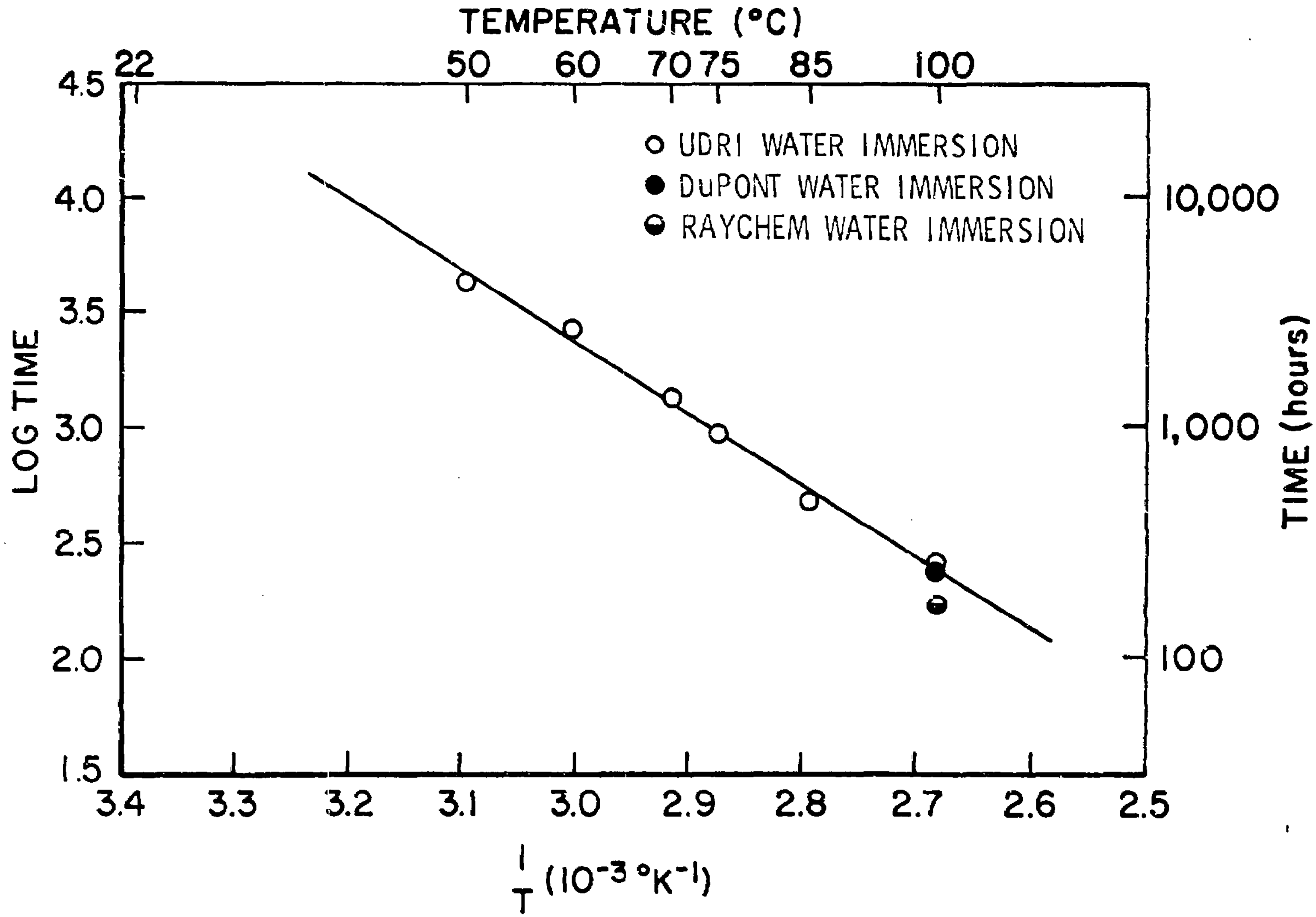


Figure 5. Effect of Temperature Upon Lifetime (20% Decrease in Tensile Strength) of Kapton Film.

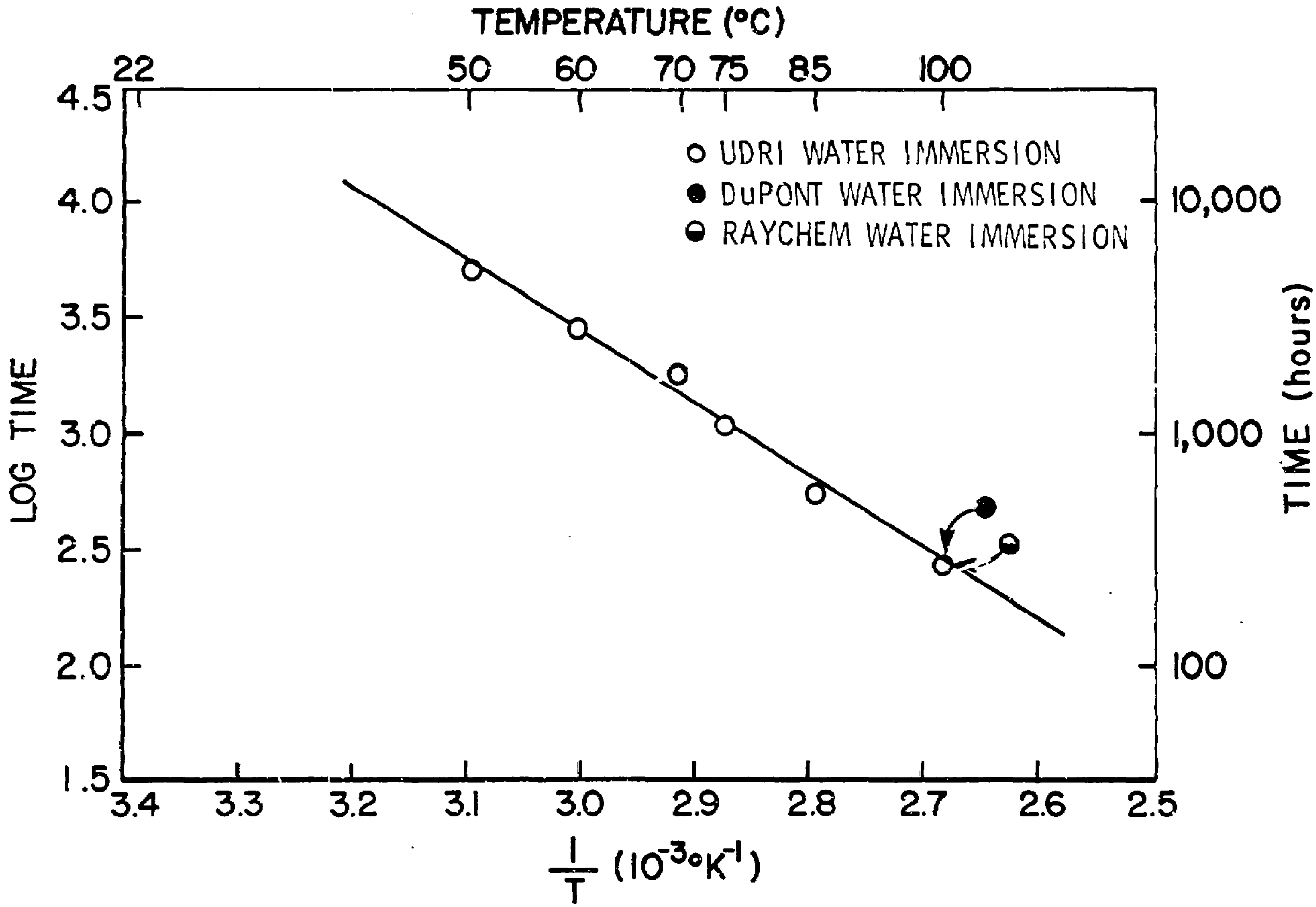


Figure 6. Effect of Temperature Upon Lifetime (50% Decrease in Tensile Elongation) of Kapton Film.

SECTION 5

STRESSED HUMIDITY EXPOSURES

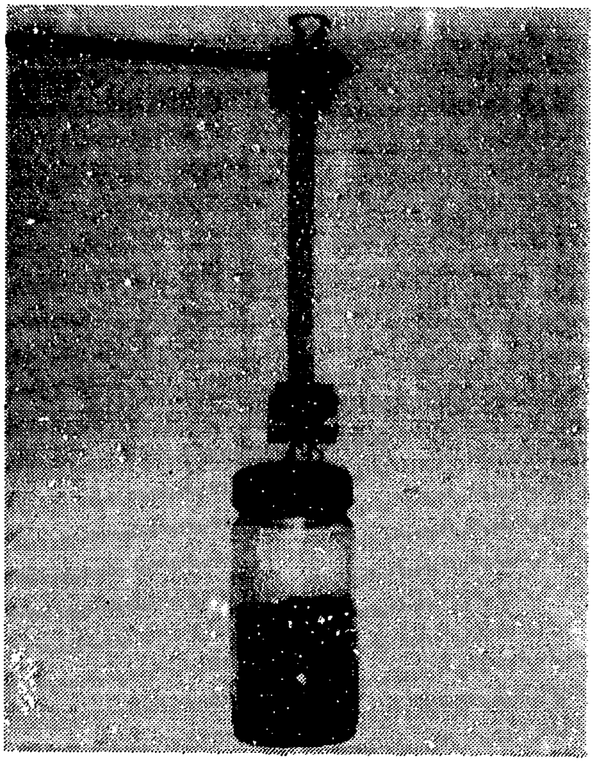
5.1 EXPOSURE AND TEST PROCEDURE

Stressed humidity exposures were conducted at two different temperatures, 75°C (167°F) and 85°C (185°F). All of the exposures were at 95-100% relative humidity (RH) and all of the specimens were under 5000 psi (34.5 MPa) stress throughout the prescribed exposure periods. Twenty inch strips of Kapton film were gripped and loaded as shown in Figure 7 during the exposures.

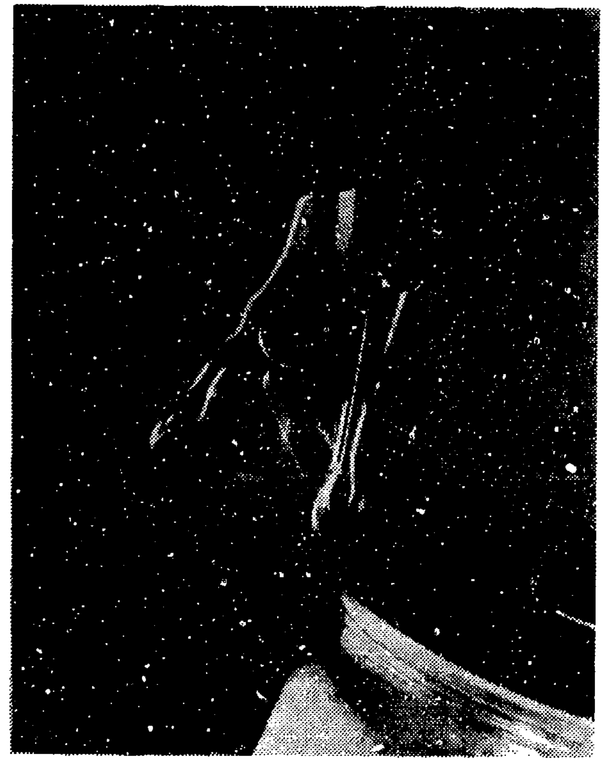
The humidity cabinet housing the specimens was checked daily for broken specimens. Subject to space limitations within the humidity cabinets, about forty to fifty specimens were started for each prescribed combination of time and temperature. At the shorter aging times, a sufficient number of specimens survived to provide an average residual strength value based on twenty "good" tensile tests (the definition of a "good" failure was presented in Section 2.2). At the longer aging times, so many specimens broke before completion of the aging period that average residual strength values had to be based on less than twenty tests. The times at which each aging failure occurred were recorded but are not presented or discussed here.

5.2 DISCUSSION OF RESULTS

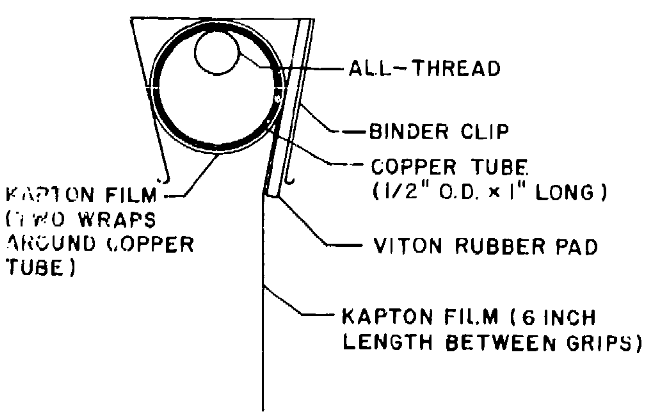
The residual property data obtained for these stressed-humidity exposures are presented in Table 2. Figures 8 and 9 illustrate these results graphically and also include the results for the unstressed water immersion exposures conducted at the same temperatures. It is



(a) Stressed Kapton Sample for Humidity Aging.



(b) Close-up of Grip Used in Humidity Cabinet for Stressed Kapton Sample.



(c) Schematic of Grip Used in Humidity Cabinet for Stressed Kapton Sample.

Figure 7. Method of Gripping and Loading Kapton Film During Stressed Humidity Exposures.

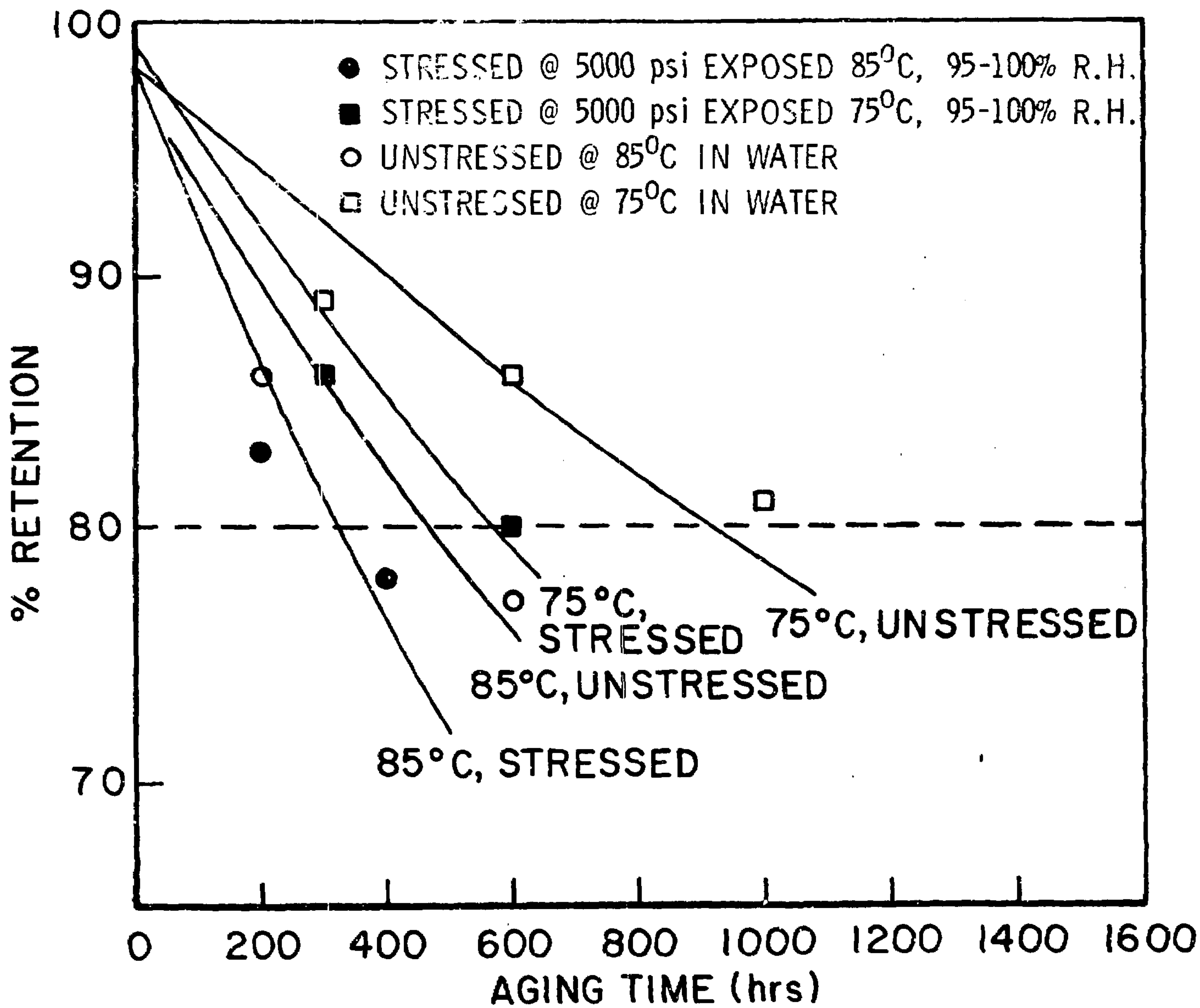


Figure 8. Effect of Stressed vs. Unstressed Environmental Aging on Tensile Strength Retention of Kapton Film.

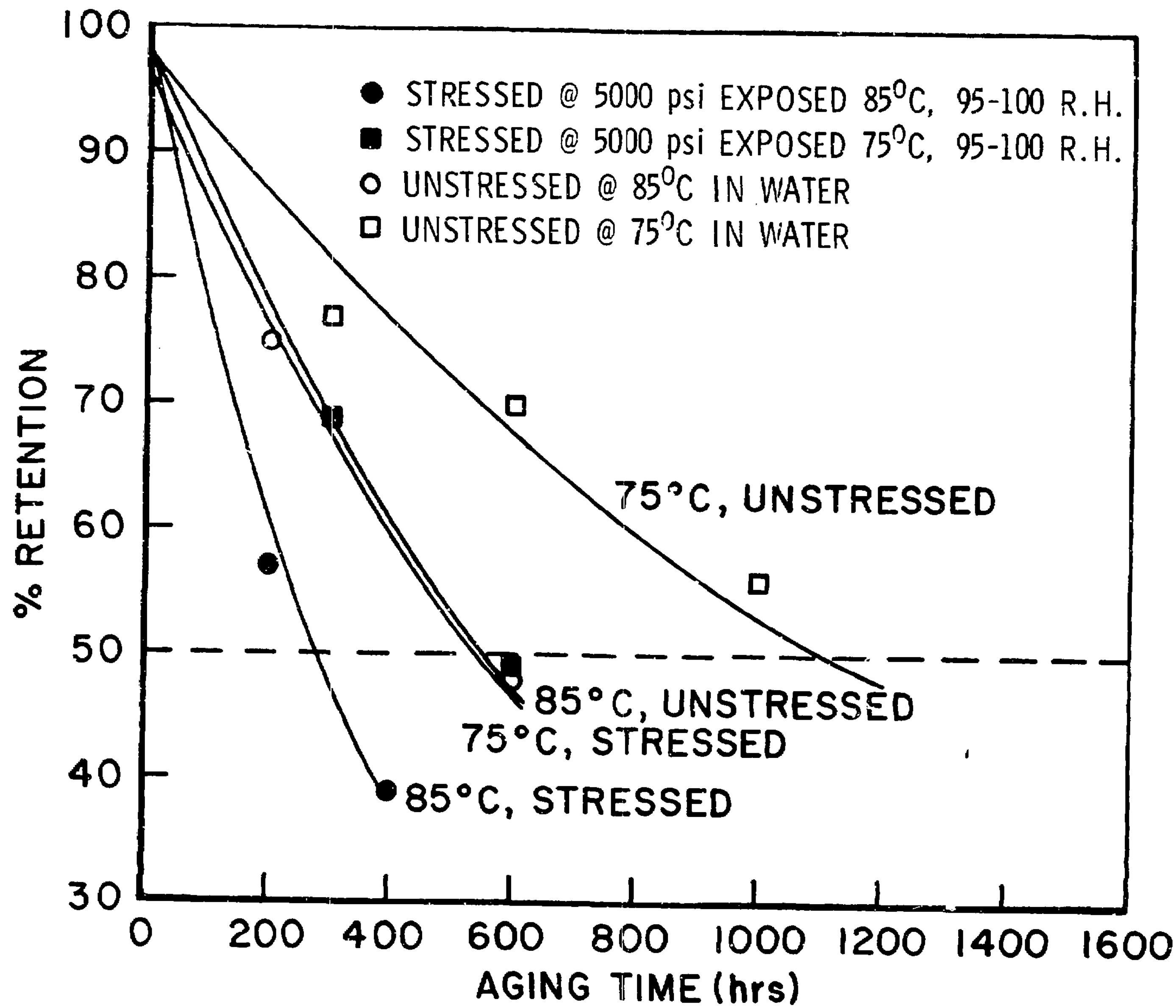


Figure 9. Effect of Stressed vs. Unstressed Environmental Aging on Retention of Tensile Elongation of Kapton Film.

apparent that the property degradation of the stressed-humidity specimens occur more rapidly than the unstressed water immersion specimens. The lifetimes (as defined previously) of the stressed-humidity specimens are only 50-75% (depending on whether strength or elongation loss is compared) of the unstressed water immersion lifetimes for equivalent temperatures. Figures 10 and 11 illustrate the position of the stressed-humidity data relative to the unstressed water immersion data on an Arrhenius plot. It can be seen from this figure that the acceleration in the rate of hydrolytic degradation observed in the stressed-humidity condition is equal to that which would be caused by an increase of about 10°C in the unstressed water immersion condition. Since the slope produced by the two stressed-humidity points is equivalent to that exhibited by the water immersion data, it can be concluded that the effect of temperature on the hydrolysis reaction rate is unaffected by the presence of mechanical stress or by the concentration of the water in the exposure environment. This latter observation is probably due to the fact that the reaction rate depends upon absorbed moisture concentration, and at equivalent temperatures, the equilibrium absorbed moisture content is equivalent for a water immersion or condensing humidity environment; the difference being reflected only in the relative length of time required to reach the equilibrium absorbed moisture content.

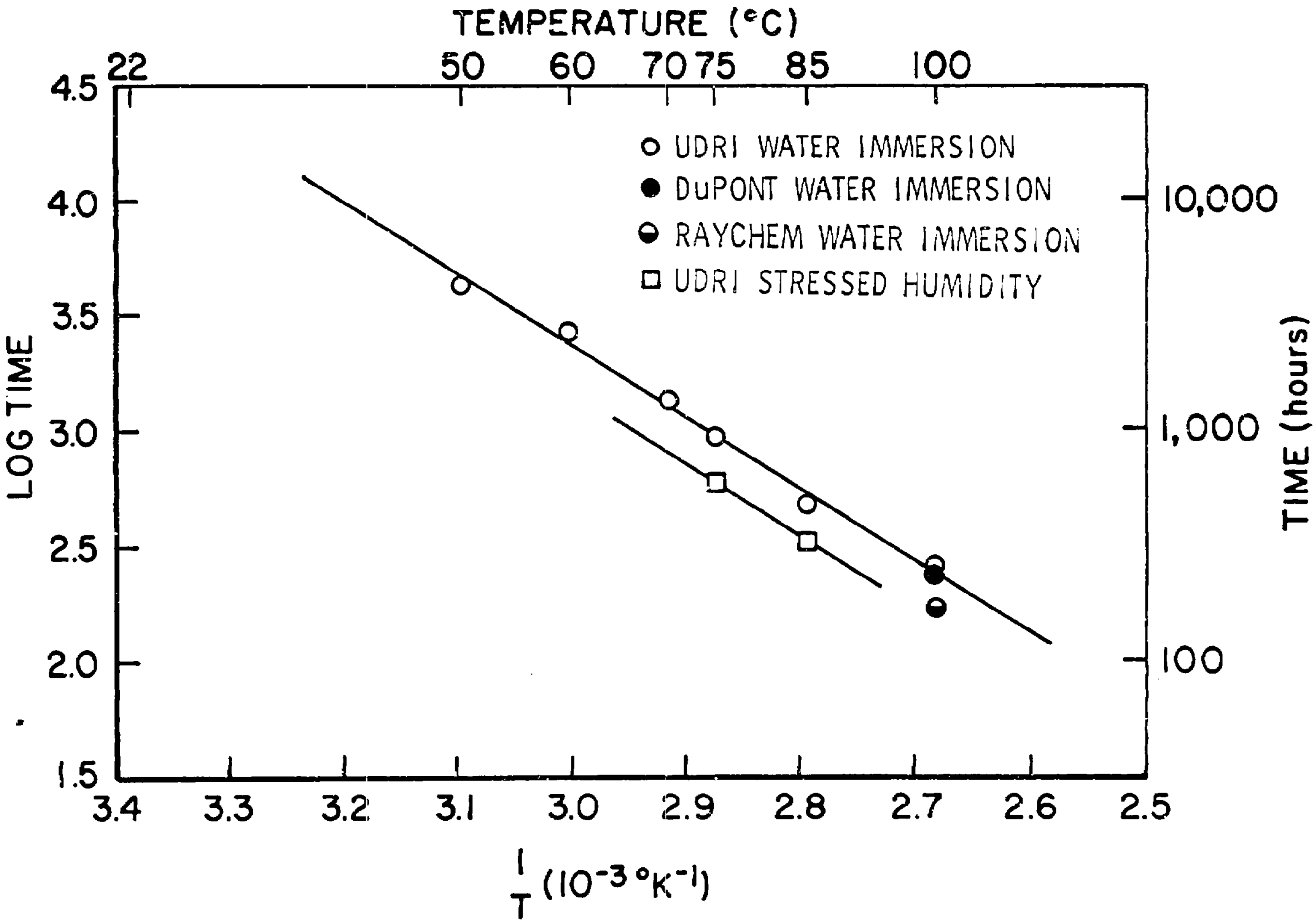


Figure 10. Effect of Temperature Upon Lifetime (20% Decrease in Tensile Strength) of Kapton Film.

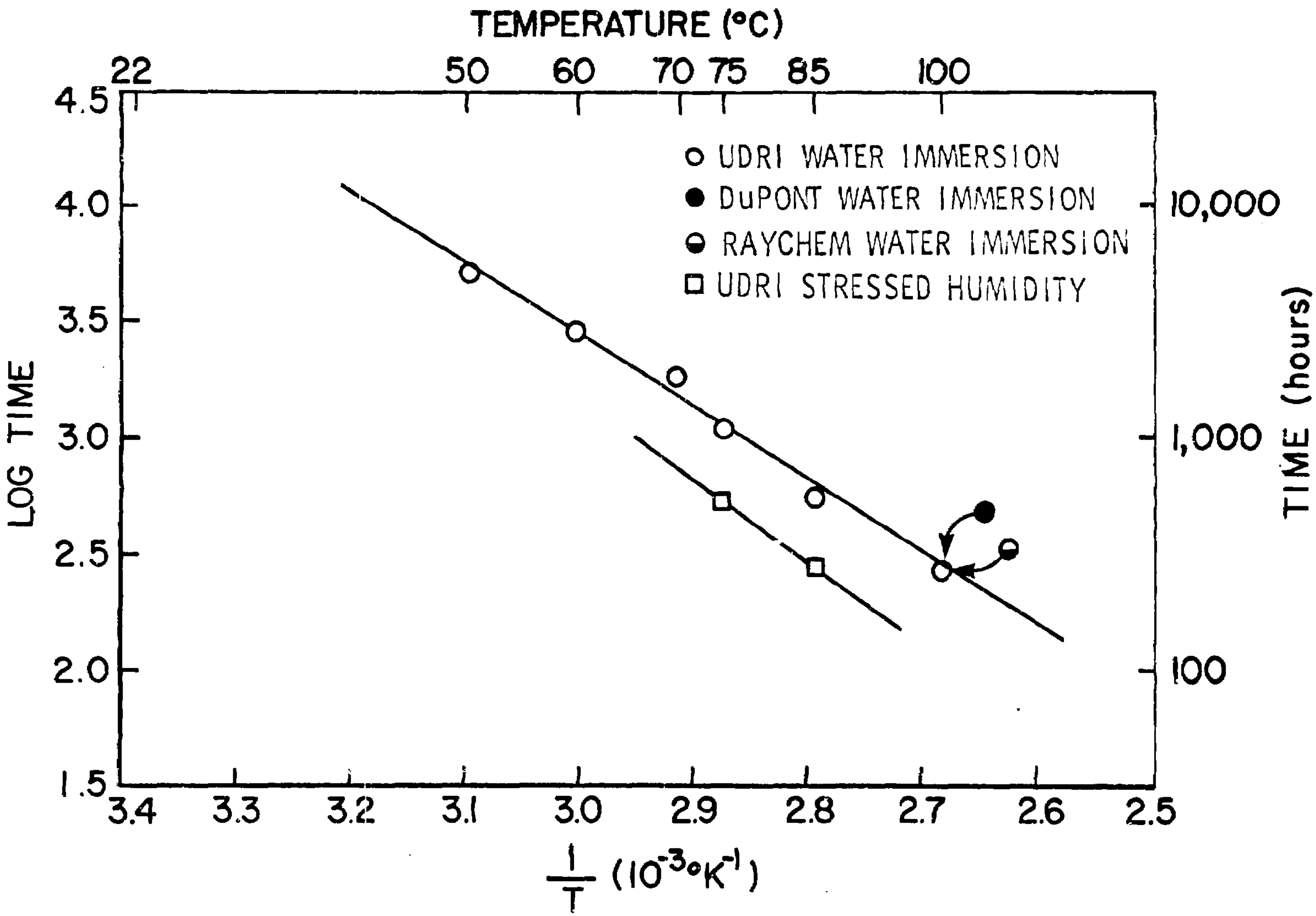


Figure 11. Effect of Temperature Upon Lifetime (50% Decrease in Tensile Elongation) of Kapton Film.

SECTION 6

UNSTRESSED HUMIDITY-ULTRAVIOLET EXPOSURES

6.1 EXPOSURE AND TEST PROCEDURE

Unstressed humidity-ultraviolet exposures were conducted in a QUV Accelerated Weathering Tester. This apparatus can be programmed to provide a 24 hour cycle comprised of any desired ratio of alternating ultra-violet (UV) light irradiation and condensation. The exposures conducted during this investigation utilized a 4 hour condensation - 8 hour UV cycle. The temperature throughout the 8-hour UV cycle was maintained between 50°C and 55°C (122°F and 131°F), except for the first 1/4-hour, during which time the temperature fell from the 56-62°C range (134-43°F) to the equilibrium range. When the UV cycle ends and the condensation cycle starts, the temperature decreased over a 1/2-hour period to about 41°C (105°F), then recovered over a 1 1/2-hour period to between 56°C and 62°C (134°F and 143°F), where it remained for the remaining 2 hours of the 4 hour cycle. Figure 12 illustrates a typical 24 hour QUV temperature record. Figure 13 illustrates the QUV test cabinet and specimen exposure arrangment.

6.2 DISCUSSION OF THE RESULTS

The residual property data for the QUV exposed specimens is presented in Table 2 and illustrated in Figures 14 and 15 , alongside the results for the unstressed water immersion specimens exposed at 60°C. It is readily noted that the property degradation of the Kapton film occurs much more rapidly in the cyclic QUV exposure environment then in a water immersion environment at an equivalent or slightly higher temperature.

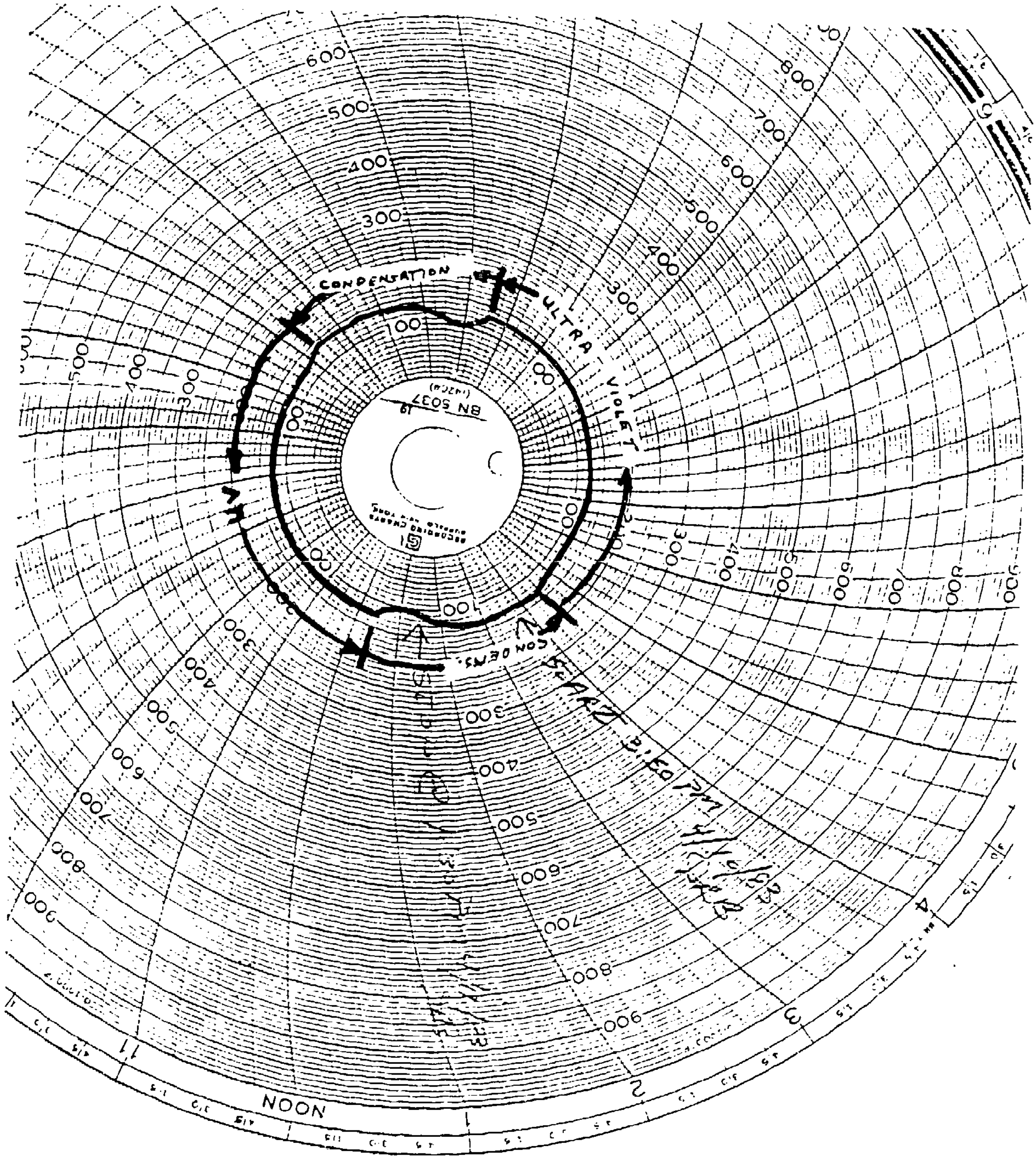
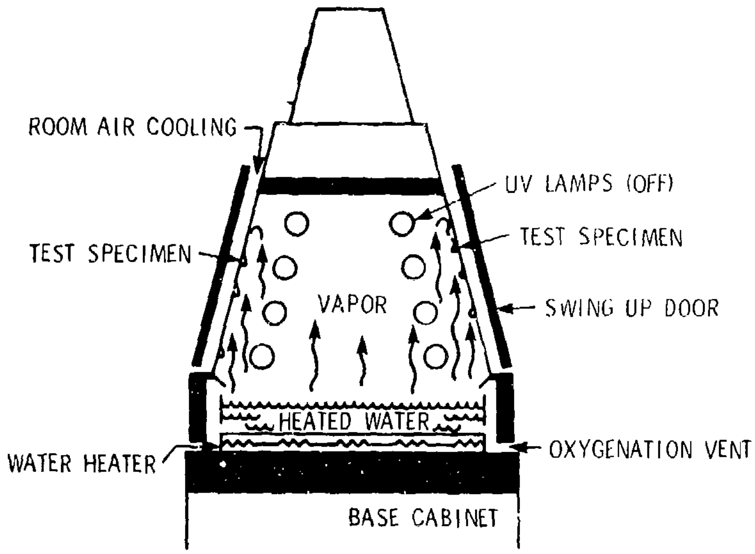


Figure 12. Typical 24 Hour QUV Cabinet Temperature Record.



(a) Simplified Cross-Section of QUV Cabinet (Condensation Period Illustrated)

(b) Mounting of Kapton Film Strips on Test Specimen Rack in QUV Cabinet.

Figure 13. QUV Accelerated Weathering Test Cabinet and Specimen Arrangement.

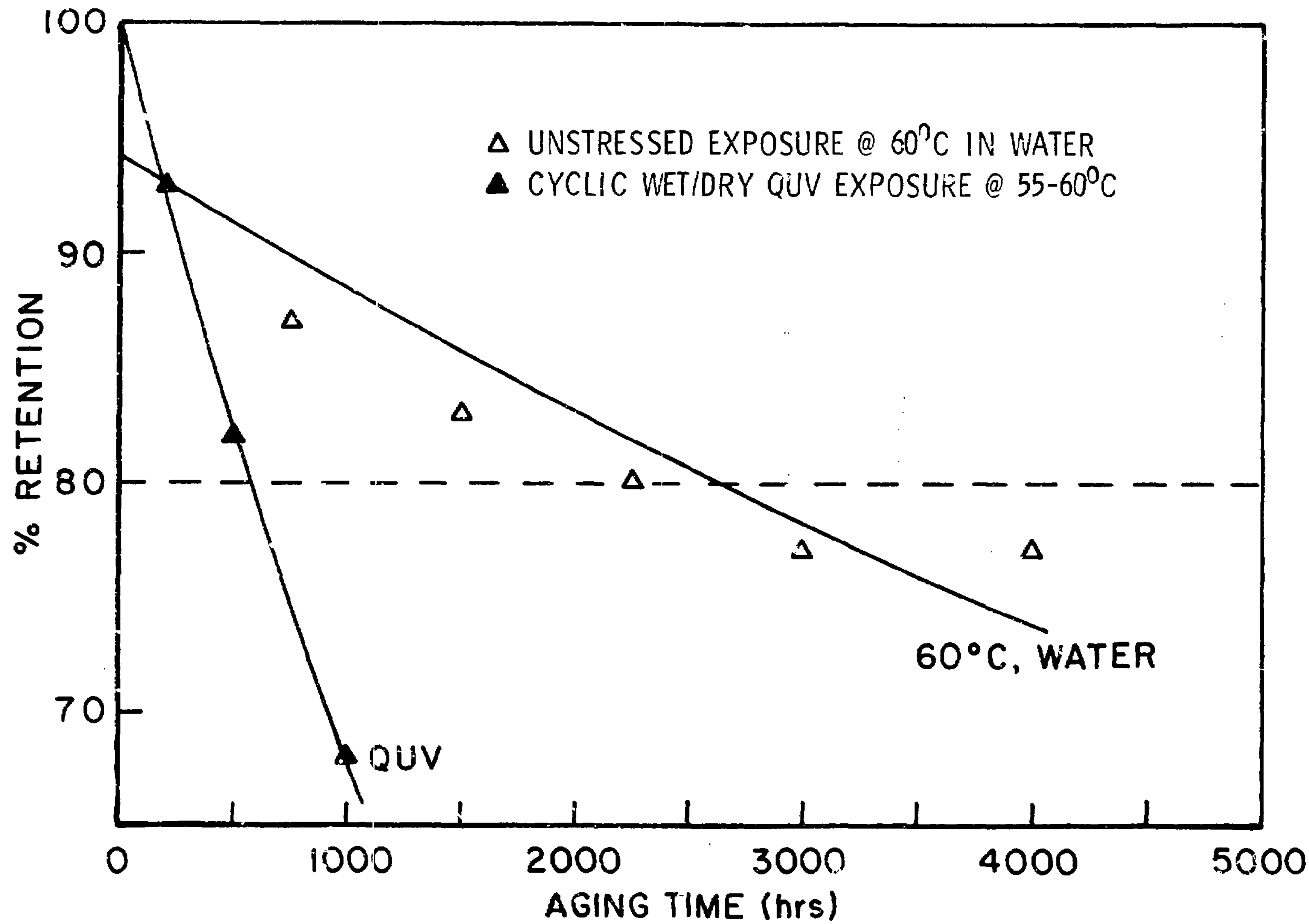


Figure 14. Effect of Unstressed Environmental Aging @ 60°C in Water vs. Cyclic Wet/Dry QUV Exposure @ 55-60°C on Retention of Tensile Strength of Kapton Film.

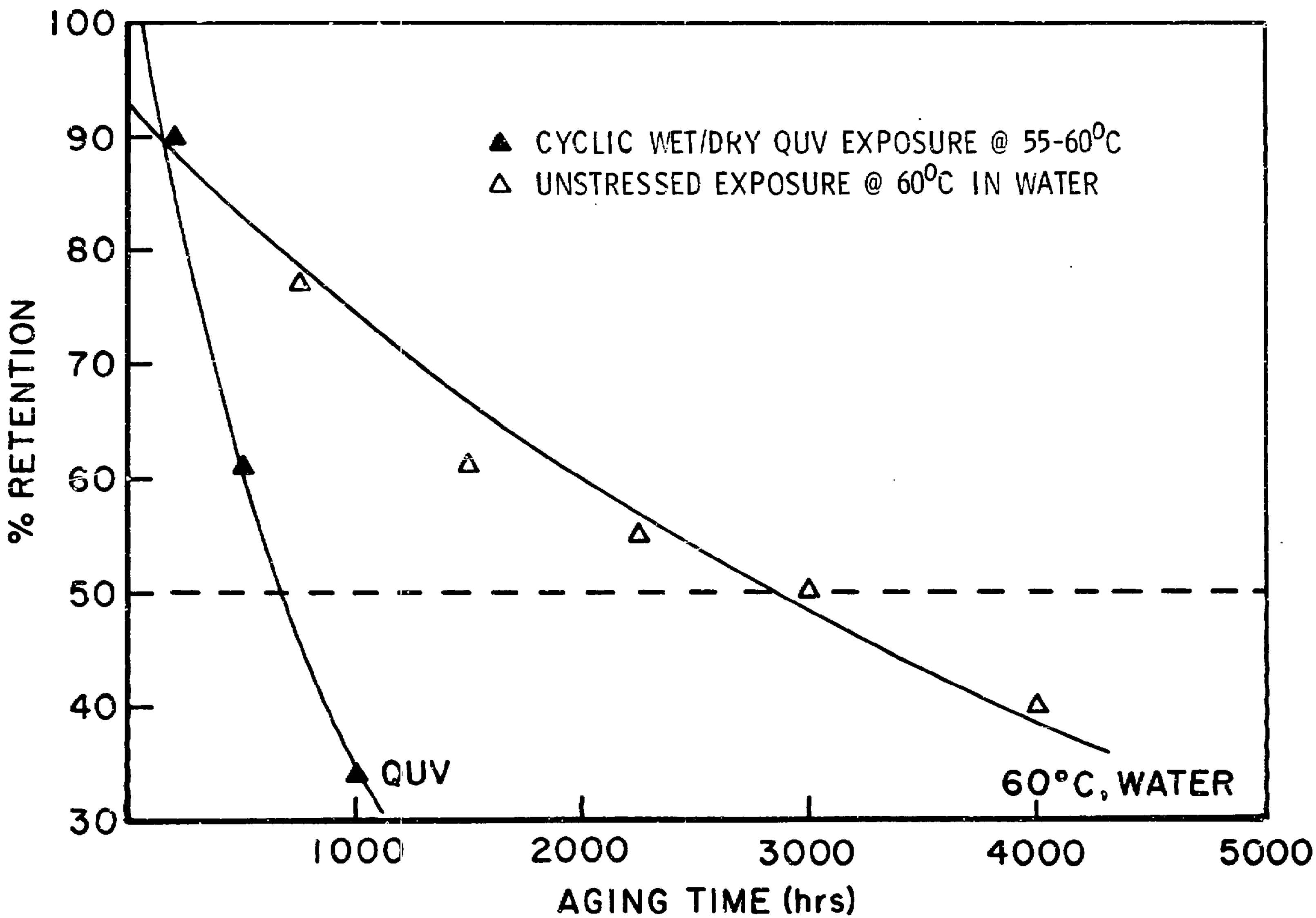


Figure 15. Effect of Unstressed Environmental Aging @ 60°C in Water vs. Cyclic Wet/Dry QUV Exposure @ 55-60°C on Retention of Tensile Elongation of Kapton Film.

The "lifetime" of the QUV specimens is less than 1/3 that of the comparable water immersion specimens.

Figures 16 and 17 illustrate the position of the QUV (plotted at T = 60°C) data relative to the unstressed water immersion data and the stressed humidity data on an Arrhenius plot. It is apparent from these figures that the rate of degradation observed in the cyclic UV-humidity condition is approximately equivalent to that which would occur at 80°C in the unstressed water condition. Since 1/3 of the QUV condition is simply condensing humidity at 60°C, it can be concluded that the acceleration in the QUV degradation rate is due to the dry ultraviolet portion of the cycle, during which time the temperature ranges between 50 and 55°C.

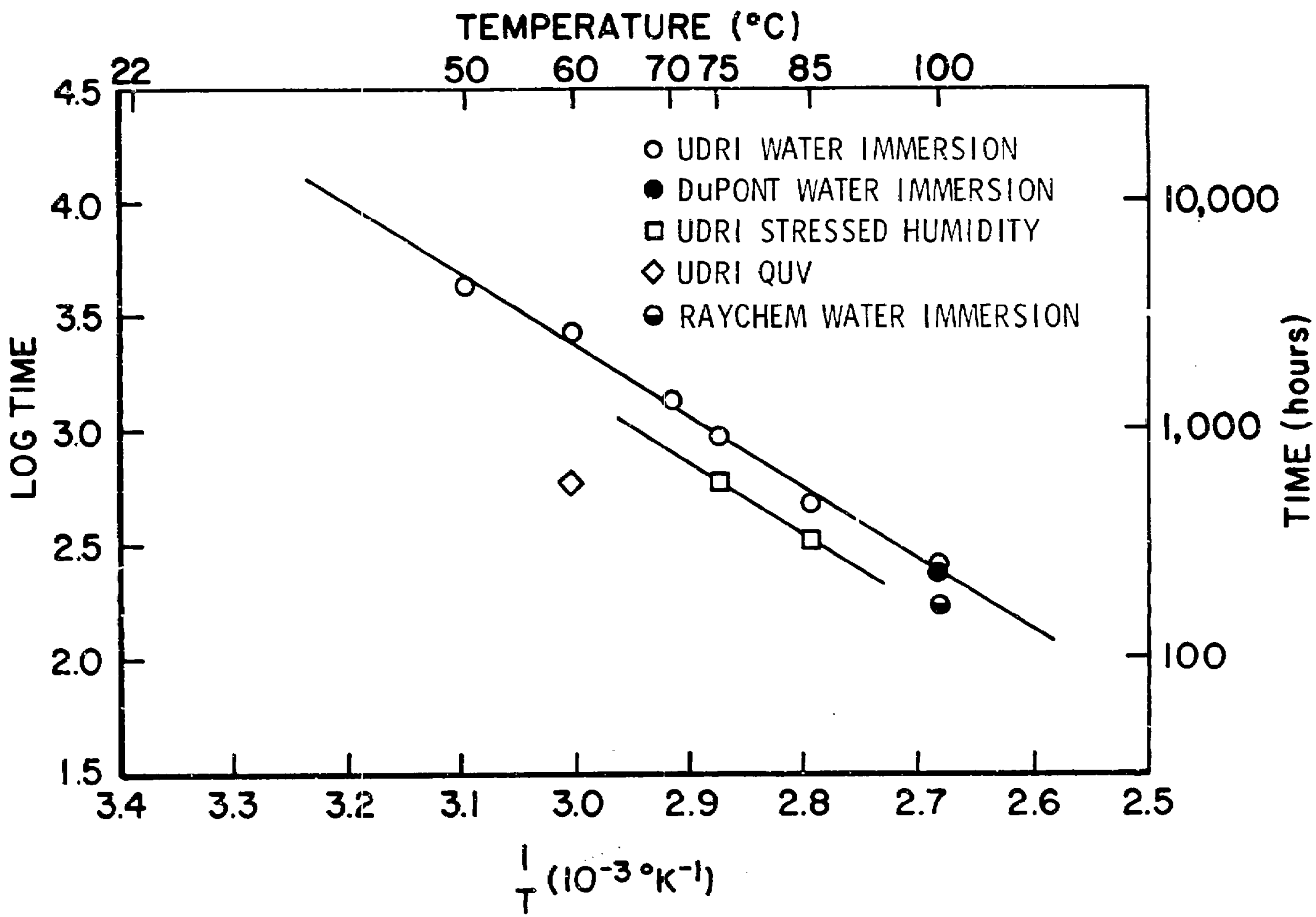


Figure 16. Effect of Temperature Upon Lifetime (20% Decrease in Tensile Strength) of Kapton Film.

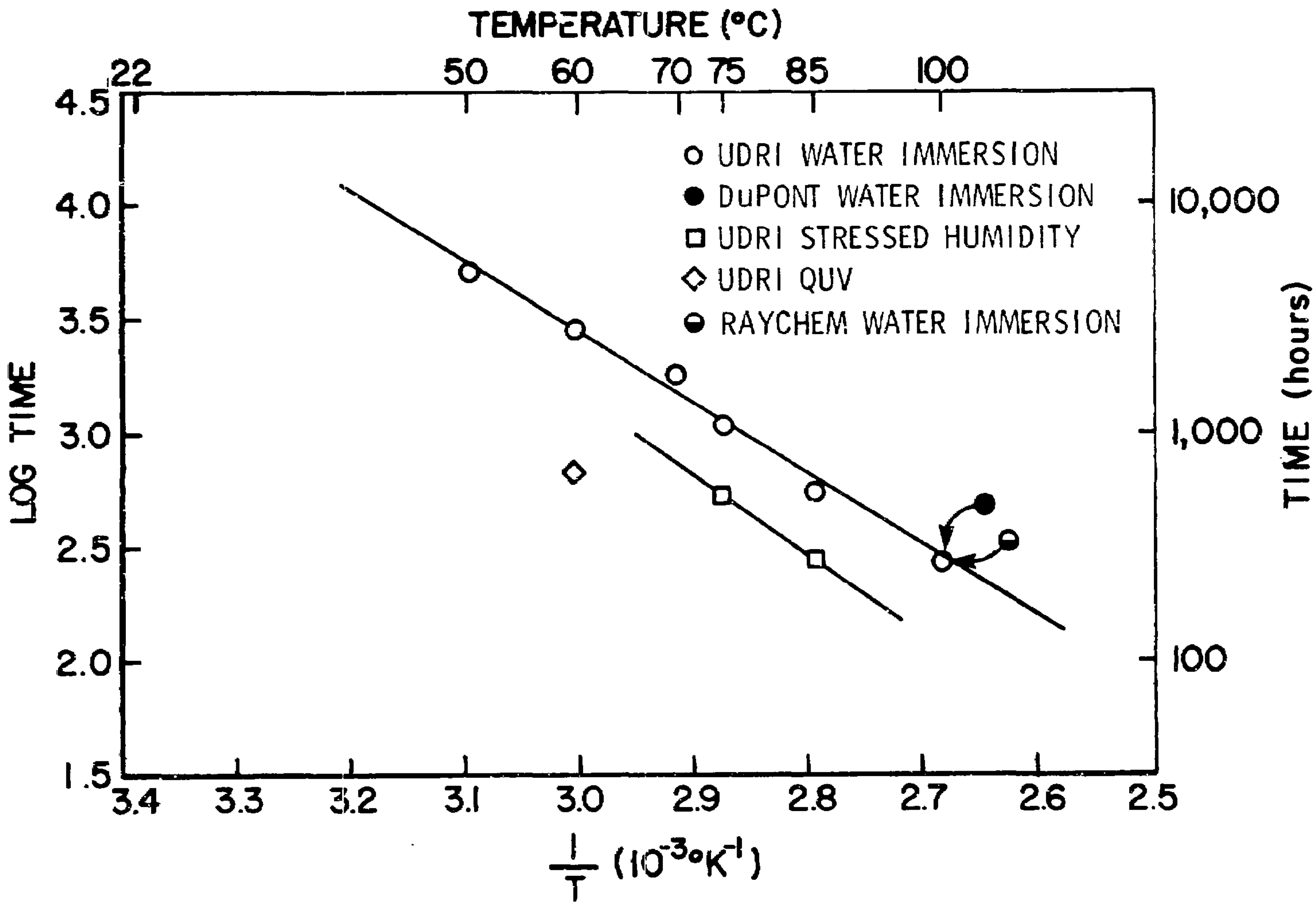


Figure 17. Effect of Temperature Upon Lifetime (50% Decrease in Tensile Elongation) of Kapton Film.

SECTION 7
CONCLUSIONS

Kapton type H film undergoes hydrolytic degradation at a rate which was found to be very well correlated to temperature by the Arrhenius relationship. Data from three previous studies[2-4] were examined and compared to that generated in this investigation. The rates of degradation determined in one of these prior studies were found to disagree considerably in magnitude from those found in the other two. The results obtained in this investigation agreed rather well with the latter two. A similar temperature dependency was found for both the results obtained here and those which exhibited the considerably different degradation rates.

While the hydrolytic degradation mechanism is not fully known and can involve a number of different degradation routes, the residual tensile strength and elongation were found to be best represented mathematically by an exponential decay function of time (first order reaction kinetics).

While the temperature range over which this data was generated was 50°C to 100°C, the excellent linearity of the Arrhenius relationship would indicate that it should be possible to extrapolate the relationship for limited distances with reasonable confidence.

The rate of degradation of Kapton H film was found to be accelerated by the imposition of a 5,000 psi (34.5 MPa) tensile stress on the film during humid aging. It was also found that the effect of temperature (over the limited temperature range examined) on degradation rate of the stressed exposures was the same as that observed for the unstressed exposures.

The rate of degradation of Kapton H film was found to be significantly accelerated by a cyclic ultraviolet-humidity exposure. This acceleration was due to the ultraviolet portion of the exposure cycle.

REFERENCES

1. Trademark, E. I. DuPont DeNemours, Inc.

2. "Hydrolysis Resistance of Kapton Polyimide Film as Aerospace Wire Insulation," Document P, Industrial Films Division, Polymer Products Department, E. I. DuPont DeNemours & Co., Inc., November 1981.

3. Germaraad, P. B. and R. S. Cornelius, "Investigation of Polyimide Wire Insulation Cracking Phenomena," Laboratory Report No. 5191, Raychem Corp., July 1982.

4. De Iasi, R. and J. Russell, "Aqueous Degradation of Polyimides," Grumman Report RM-504, April 1971.

5. Welch, G. L. and L. R. Lofgreen, "Using Accelerated Hydrolytic Reversion Data to Predict Service Life of Elastomeric Potting Compounds," AFML-TR-70-297, February 1971.

6. Berner, W. E., "A Method to Predict the Service Life of Internal Fuel Cell Baffle Materials," AFML-TR-73-278, January 1974.

7. Chartoff, R. P. and T. W. Chin, "A Study of Crosslinking in Polyimides by Viscoelastic and Diffusion Techniques," Polymer Engineering and Science, Vol. 20, No. 4, March 1980.

8. Wallach, M. L., Journal of Polymer Science, A-2, 953 (1968).

APPENDIX

COMPLETE TEST DATA

Tables A.1 through A.10 presents the complete tensile test data obtained during this program. Values labeled N.G. represent specimens which failed at the grip edge during tensile testing and which produced strength or elongation values lower than the average values.

Table A.11 presents tensile data presented by DuPont from the same mill roll as that from which all our specimens came.

The average values presented at the bottom of each column of data in these tables are summarized in the text.

TABLE A.1

CONTROL PROPERTIES OF UNAGED KAPTON FILM

Specimen No.	ROLL C Tensile Strength (10^3psi)	ROLL C Ult. Elong. (%)	ROLL C Test Result	ROLL D Tensile Strength (10^3psi)	ROLL D Ult. Elong. (%)	ROLL D Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	36.0	65.0		29.5	39.0							
2	33.7	59.0		34.3	61.0							
3	32.5	31.0		36.7	73.0							
4	32.2	46.0		27.8	31.0							
5	31.6	44.0		29.4	39.0							
6	25.2	56.0		36.0	70.0							
7	36.0	64.0		32.7	54.0							
8	35.2	56.0		33.5	56.0							
9	33.6	48.0		31.0	45.0							
10	37.8	64.0		37.5	74.0							
11	34.0	47.0		31.5	49.0							
12	33.5	50.0		32.3	52.0							
13	38.5	69.0		33.3	57.0							
14	31.3	34.0		28.2	34.0							
15	33.7	49.0		32.3	54.0							
16	35.2	56.0		32.7	54.0							
17	36.5	62.0		31.5	46.0							
18	35.0	57.0		33.5	55.0							
19	36.3	63.0		35.0	60.0							
20	32.3	44.0		33.4	54.0							
21	34.5	48.0		32.4	51.0							
22	37.3	58.0		31.6	51.0							
23	37.2	59.0		33.0	55.0							
24	36.6	58.0		32.0	49.0							
25	36.5	59.0		35.4	64.0							
26	34.5	49.0		32.6	50.0							
27	31.0	38.0		32.6	54.0							
28	34.1	52.0		34.6	63.0							
29	32.1	44.0		33.0	54.0							
30	35.5	58.0		33.3	58.0							
31	35.2	58.0										
22												
Avg.	34.5	54.2		32.6	52.9							
Std.Dev.	2.0	[illegible]		2.6	11.8							

(1) Each roll represents an adjacent slit lane from Mill Roll 07792.

TABLE A.2

RESIDUAL PROPERTIES OF KAPTON FILM AFTER WATER IMMERSION AT 100°C

Specimen No.	24 Hr Immersion Tensile Strength (10^3psi)	24 Hr Immersion Ult. Elong. (%)	24 Hr Immersion Test Result	112 Hr Immersion Tensile Strength (10^3psi)	112 Hr Immersion Ult. Elong. (%)	112 Hr Immersion Test Result	184 Hr Immersion Tensile Strength (10^3psi)	184 Hr Immersion Ult. Elong. (%)	184 Hr Immersion Test Result	376 Hr Immersion Tensile Strength (10^3psi)	376 Hr Immersion Ult. Elong. (%)	376 Hr Immersion Test Result
1	28.4	30		30.7	43		26.1	19	N.G.	27.7	28	
2	31.7	42		27.4	28		29.3	30		27.2	25	
3	33.6	51		24.5	18		28.0	24		28.0	30	
4	31.1	40		27.9	30	N.G.	28.3	28		22.8	13	
5	31.5	44		26.9	27		27.3	24	N.G.	27.1	26	
6	28.8	30	N.G.	26.2	24		27.0	26		28.1	30	
7	29.5	36		29.3	40		28.9	30		27.0	26	
8	32.6	46		26.4	28		27.6	29		25.2	13	N.G.
9	32.7	46		27.6	35	N.G.	28.8	34		25.3	18	
10	31.5	43		24.6	22	N.G.	29.0	32		27.3	24	
11	32.7	48		26.5	26		29.0	32		27.0	27	
12	31.9	43		27.6	32		29.1	32		26.9	26	
13	31.1	42		25.7	22		26.4	—	N.G.	27	26	
14	34.2	54		26.9	30	N.G.	28.2	28		27.6	28	
15	30.6	40		26.2	28	N.G.	28.9	28		26.1	23	N.G.
16	32.6	48		28.8	36		28.0	26	N.G.	27.0	26	
17	28.5	34		27.4	28	N.G.	29.2	28	N.G.	25.0	19	N.G.
18	27.8	33		28.2	34		29.0	30		24.2	17	N.G.
19	34.6	56		28.3	30		27.5	22		25.6	22	
20	32.4	46		27.6	34		27.8	26		25.9	23	N.G.
21	32.9	49		28.6	37		24.0	16		25.0	20	
22				29.0	36		25.3	20	N.G.	25.1	22	
23				26.9	23	N.G.	26.2	22	N.G.	25.2	22	
24				30.0	41		27.1	24		23.0	14	N.G.
25				28.0	35	N.G.	28.6	28		26.2	25	
26				30.0	42		28.8	28		27.3	30	
27				27.1	27	N.G.	29.3	30				
28				29.3	37							
29				29.2	36							
30												
31												
32												
Avg.	31.6	44		28.0	33		28.2	28		26.5	25	
Std.Dev.	1.9	7		1.6	7		1.2	4		1.3	4	

TABLE A.3

RESIDUAL PROPERTIES OF KAPTON FILM AFTER WATER IMMERSION AT 85°C

Specimen No.	200 Hr. Immersion			600 Hr. Immersion								
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	29.3	38		27.8	30.6							
2	29.3	37		26.1	24.0							
3	30.3	43		25.0	20.0							
4	27.8	32		26.7	26.8							
5	29.8	43		27.2	31.8							
6	29.4	39		25.8	26.4							
7	30.4	44		25.4	24.6							
8	30.2	41		24.9	19.2	N.G.						
9	30.3	42		26.4	28.2							
10	29.6	40		27.7	30.0							
11	28.5	35	N.G.	26.1	22.2							
12	30.0	42		26.1	22.0							
13	29.4	38		26.8	26.2							
14	30.8	46		26.9	30.4							
15	28.9	37	N.G.	26.1	22.8							
16	27.4	27		26.7	25.2							
17	30.2	43		28.2	31.3							
18	28.5	35	N.G.	27.3	28.6							
19	30.3	46		26.7	26.6							
20	27.3	26	N.G.	26.4	24.0							
21	31.8	47		24.9	21.8							
22	30.3	41		26.9	28.2							
23	30.0	38		24.3	18.4							
24	30.3	42		26.8	27.9							
25	30.8	44		25.1	21.2							
26	30.0	42		25.2	20.0							
27	30.2	40		26.2	26.2							
28	30.3	45		26.8	27.6							
29	31.5	48		26.6	27.4							
30	29.6	40		[illegible]	22.4							
31	29.0	38		25.4	23.0							
32	27.5	[illegible]		26.5	27.4							
33	30.3	44										
34	29.3	[illegible]										
[illegible]	29.8	40.5		26.5	26.2							
[illegible]	1.0	4.8		[illegible]	3.5							

TABLE A.4

RESIDUAL PROPERTIES OF KAPTON FILM AFTER WATER IMMERSION AT 75°C

Specimen No.	300 Hr. Immersion			600 Hr. Immersion			900 Hr. Immersion					
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	32.2	47.8		30.0	41.0		27.9	31.6				
2	31.3	45.0		28.6	33.0		28.8	36.5				
3	31.8	48.6		29.4	35.9		27.2	28.2				
4	30.7	41.0	N.G.	31.6	44.6		27.8	31.0				
5	28.2	29.0		29.5	34.2		27.0	26.4				
6	31.1	44.4		29.8	37.2		28.6	31.2				
7	30.7	52.6		29.0	35.0		26.4	24.0				
8	31.5	46.4		30.2	40.5		28.0	31.0				
9	32.3	53.0		30.4	40.0		29.7	37.6				
10	31.2	44.0		27.0	27.0		27.2	27.5	N.G.			
11	30.1	36.0	N.G.	28.2	32.5		27.7	28.6				
12	31.6	43.0		29.5	33.0		27.8	28.2				
13	32.7	50.6		29.0	34.0		26.3	23.0	N.G.			
14	30.0	38.0		29.5	38.2		28.0	28.5				
15	30.1	40.0		31.0	43.0		27.1	24.2	N.G.			
16	29.3	35.0		29.2	38.0		27.2	26.8				
17	30.1	40.6	N.G.	30.8	45.0		26.3	23.0	N.G.			
18	31.1	46.0		29.5	39.5		28.3	31.5				
19	31.8	48.5		30.2	41.8		28.1	31.0				
20	28.2	30.5		26.2	23.5		26.2	23.5	N.G.			
21	29.3	34.0		30.2	45.0		25.3	21.4	N.G.			
22	27.7	27.6		31.0	45.0		27.4	30.2				
23	29.4	37.4		25.0	22.2		25.8	23.9	N.G.			
24	33.2	55.5		29.2	38.2		26.6	29.0	N.G.			
25	28.3	31.6		30.8	44.5		26.2	25.0				
26	29.2	37.2					25.5	22.0	N.G.			
27	31.1	46.0					26.5	25.2				
28	32.6	54.0					28.5	34.3				
29	32.1	52.0					29.2	39.5				
30	29.6	41.0					29.0	39.0				
Avg.	30.6	42.0		29.5	37.8		27.8	30.3				
S.D.	1.5	7.8		1.3	6.1		0.9	4.2				

TABLE A.5

RESIDUAL PROPERTIES OF KAPTON FILM AFTER WATER IMMERSION AT 70°C

Specimen No.	500 Hr. Immersion			1000 Hr. Immersion			1500 Hr. Immersion					
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	31.6	44.0	N.G.	31.3	46.2		26.8	26.6	N.G.			
2	33.6	53.6		30.8	46.4		28.5	39.0				
3	32.8	49.2		28.1	33.6		27.1	20.2				
4	32.0	46.0		28.9	39.2		27.8	32.4				
5	29.4	40.0		26.3	26.0		27.2	27.2				
6	26.6	40.0	N.G.	27.2	32.6		27.2	28.4				
7	30.5	69.0		29.2	42.8		25.8	21.4				
8	30.0	44.0	N.G.	27.6	32.0		27.8	27.0	N.G.			
9	29.4	39.0		29.8	39.6		27.2	24.0				
10	34.0	54.0		30.2	43.4		28.4	34.0				
11	30.5	39.0		26.3	25.2		28.0	30.0				
12	30.2	40.0		30.5	45.6		28.5	34.8				
13	30.3	40.0		28.7	37.2		28.8	33.6				
14	30.3	42.0		28.8	40.0		26.7	25.0				
15	32.5	51.0		28.5	39.0		26.3	24.0				
16	28.0	31.0		24.8	20.0		27.9	32.2				
17	29.5	38.0		29.7	44.8		26.5	23.6				
18	31.5	46.8		28.9	38.8		27.9	30.8				
19	33.6	59.2		27.9	34.0		29.2	37.2				
20	32.6	53.4		30.4	46.6		29.2	36.4				
21	31.6	49.0		26.5	28.0		28.3	32.4				
22	31.6	47.0		27.7	34.8		25.6	22.0				
23	26.0	22.0		29.1	42.0		26.6	27.8				
24	31.5	46.0		29.8	44.8		26.2	23.4				
25	29.4	33.6		27.6	35.5		29.1	39.4				
26	32.0	47.0		29.7	45.8		28.1	34.8				
27	29.5	39.6		28.7	39.4		26.2	24.8				
28	30.6	45.6		26.9	30.4		27.4	29.8				
29	27.0	27.0		26.5	31.8		28.2	28.0				
30	32.0	50.0		28.8	43.2		28.8	36.6				
31	31.4	46.0		27.2	35.0		28.1	32.0				
32							26.8	27.4				
							26.8	27.0				
Avg.	31.0	45.9		28.7	37.7		27.6	29.9				
Std.Dev.	2.0	10.2		1.7	7.6		1.1	5.3				

TABLE A.6

RESIDUAL PROPERTIES OF KAPTON FILM AFTER WATER IMMERSION AT 60°C

Specimen No.	[illegible] Hr. Immersion			1500 Hr. Immersion			[illegible] Hr. Immersion			[illegible] Hr. Immersion			[illegible] Hr. Immersion		
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	27.8	31.2		28.0	29.0	N.G.	22.5	17.6		27.8	3[illegible].6		[illegible]	17	
2	30.3	47.2		27.8	28.0		26.9	25.4	N.G.	28.1	30.0		25.2	22	
3	28.2	32.6		28.8	32.0	N.G.	28.4	33.5		26.8	25.4		25.8	20	N.G.
4	30.0	41.4		28.7	28.0		28.4	33.8		27.5	[illegible]		27.4	26	
5	30.2	43.4		29.2	34.0	N.G.	27.4	26.5	N.G.	26.4	24.6	N.G.	[illegible]	[illegible]	N.G.
6	28.1	31.4		24.3	15.0		27.3	24.2	N.G.	27.2	[illegible]		27.8	18	N.G.
7	31.1	46.2		26.0	21.0		28.7	32.4		27.2	28.[illegible]		28.1	26	
8	29.3	49.4		29.4	34.0		29.4	36.6		27.4	20.0		24.3	14	
9	30.8	46.8		27.0	26.0		27.6	28.0		23.3	14.[illegible]		[illegible]	2[illegible]	
10	27.9	31.6		28.3	32.0		26.8	25.5		25.3	21.9		27.3	26	
11	30.3	42.8		29.8	40.0		27.3	26.8	N.G.	26.7	22.2		26.2	20	N.G.
12	31.2	48.0		28.4	35.0		28.5	31.8		27.3	31.4		26.[illegible]	20	N.G.
13	32.1	48.2		29.3	37.0		26.9	24.6	N.G.	25.8	23.0		26.2	20	N.G.
14	29.5	43.0		29.5	37.0		27.9	29.0		28.3	37.8		[illegible]	16	N.G.
15	32.6	57.0		29.6	38.0		25.9	20.8	N.G.	25.8	23.5		25.8	28	
16	31.3	47.2		30.6	42.0		28.0	20.7		27.2	29.8		25.8	16	
17	30.2	42.6		29.5	37.0		25.2	20.6	N.G.	27.5	30.[illegible]		24.[illegible]	14	
18	29.9	40.4		28.0	26.0		29.2	33.4		27.0	27.2		[illegible]	16	
19	27.7	34.4		28.6	33.0		24.8	17.5		26.3	26.8		28.[illegible]	24	
20	29.4	42.8		28.4	33.0		26.8	26.2		25.0	18.5		26.2	19	N.G.
21	29.1	40.0		28.7	35.0		26.1	24.2		27.2	28.6		28.3	24	
22	27.5	31.4		30.2	44.0		28.3	36.8		27.2	27.[illegible]		[illegible]	28	
23	[illegible]	41.6		29.0	35.0		24.8	20.0	N.G.	27.0	27.8		[illegible]	33	
24	30.4	46.8		30.0	39.0		26.2	24.6	N.G.	24.2	16.5		24.[illegible]	16	
25	31.3	48.4		30.5	41.0		28.4	36.6					27.[illegible]	22	
26	28.2	37.0		29.4	38.0		27.4	32.0					27.8	23	
27	31.2	48.8		28.7	33.0		26.8	25.4					26.[illegible]	22	
28	31.[illegible]	52.6		26.6	23.0		27.7	30.0					27.[illegible]	21	
29	30.7	46.9		28.3	32.0		29.1	36.8					24.2	17	
30	25.3	23.0		27.5	29.0		25.9	22.5							
31	26.7	2[illegible].6		29.4	37.0		26.7	24.8							
32	[illegible]	37.4		27.0	26.0		28.6	32.6							
33	28.9	38.2		28.7	34.0		27.8	25.7							
34	[illegible]	41.0		25.0	29.0		29.3	38.2							
35	31.[illegible]	21.6		23.0	28.0		[illegible]	36.0							
36	31.[illegible]	50.6					27.3	26.5							
37							27.2	27.2							
38							28.3	32.5							
Avg.	[illegible]	41.[illegible]		28.5	3[illegible].9		27.[illegible]	29.[illegible]		26.7	27.1		26.[illegible]	21.6	
S.D.	1.4	6.8		1.[illegible]	[illegible].1		1.[illegible]	[illegible]		1.2	[illegible]		[illegible]	[illegible]	

TABLE A.7

RESIDUAL PROPERTIES OF KAPTON FILM AFTER WATER IMMERSION AT 50°C

Specimen No.	1000 Hr. Immersion Tensile Strength (10^3psi)	1000 Hr. Immersion Ult. Elong. (%)	1000 Hr. Immersion Test Result	2000 Hr. Immersion Tensile Strength (10^3psi)	2000 Hr. Immersion Ult. Elong. (%)	2000 Hr. Immersion Test Result	3500 Hr. Immersion Tensile Strength (10^3psi)	3500 Hr. Immersion Ult. Elong. (%)	3500 Hr. Immersion Test Result	4000 Hr. Immersion Tensile Strength (10^3psi)	4000 Hr. Immersion Ult. Elong. (%)	4000 Hr. Immersion Test Result
1	27.4	23.0		31.2	43.8		28.7	33.6				
2	30.7	40.4		28.8	30.6		31.7	44.4				
3	31.7	50.0		32.2	53.6		30.1	40.3				
4	30.9	45.4		26.6	27.0		29.8	32.6				
5	29.1	40.0		31.1	48.8		30.2	41.0				
6	31.7	50.0		30.2	43.5		27.6	35.0	N.G.			
7	26.4	27.0		30.5	45.5		29.3	43.2				
8	33.0	58.4		29.9	40.5		29.3	39.4				
9	29.7	43.0		28.2	30.6		24.8	21.0				
10	30.7	47.6		30.2	40.5		27.3	29.5				
11	27.5	33.2		29.9	38.8		29.9	42.6				
12	31.2	50.0		30.8	43.0		30.2	41.5				
13	30.2	45.0	N.G.	30.1	41.4		29.0	38.4				
14	30.5	47.6		30.2	42.4		26.3	25.4				
15	30.3	41.4		29.6	42.0		29.5	44.0				
16	33.3	54.0		32.3	52.6		30.0	47.0				
17	38.8	33.2		28.2	30.2	N.G.	28.8	40.6				
18	32.7	50.6		31.3	43.2		29.8	37.5				
19	32.2	50.0		28.7	31.0		27.2	27.6				
20	33.0	55.4		32.3	52.2		28.3	30.6				
21	31.8	51.2		32.8	51.0		28.2	30.3				
22	27.3	32.4		32.3	49.4		30.0	39.4				
23	31.7	53.2		30.9	42.0		30.3	40.0				
24	30.2	47.4		29.7	38.6		30.6	42.0				
25	27.8	37.0		29.8	39.8		30.5	[illegible]				
26	31.2	49.6		29.1	34.6		29.0	37.8				
27	30.7	49.4		27.4	30.0		26.2	24.8				
28	29.4	42.8		31.2	46.2		27.4	31.0				
29	30.5	45.0		32.2	51.8		28.7	36.4				
30	32.6	56.0		31.8	49.0							
31	29.6	42.6		30.7	44.8							
32				30.1	46.0							
33				30.9	43.4							
34				31.4	31.5							
35				30.1	40.8							
36				32.4	56.2							
AVG.	30.6	45.2		30.3	42.1		28.9	36.0				
S.D.	[illegible]	8.7		1.5	7.7		1.6	7.2				

TABLE A.8

RESIDUAL PROPERTIES OF KAPTON FILM AFTER UNSTRESSED EXPOSURE TO ULTRAVIOLET AND HUMIDITY IN QUV CABINET

Specimen No.	200 Hr. Exposure			500 Hr. Exposure			1000 Hr. Exposure					
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	32.4	44.8		27.8	26.4		24.1	17.2				
2	35.1	50.2		31.0	43.2		24.2	19.6				
3	32.3	45.6		23.3	13.8		23.2	16.4				
4	33.3	55.2		29.8	35.6		23.3	19.0				
5	32.7	57.0		28.2	34.3		23.2	17.4				
6	32.1	54.8		24.7	20.5	N.G.	23.0	18.8				
7	32.3	58.0		27.9	33.2		22.4	15.0				
8	30.3	42.2		24.4	19.0	N.G.	22.8	16.2				
9	30.2	39.8		27.2	28.8	N.G.	23.1	19.3				
10	32.1	49.0		27.8	32.0		21.6	13.0	N.G.			
11	30.3	41.8		26.7	27.6	N.G.	23.1	16.8	N.G.			
12	32.3	50.4		27.4	29.4	N.G.	22.8	17.7				
13	29.8	41.2		29.0	34.8		23.2	18.9				
14	31.6	46.8	N.G.	27.0	35.4		22.3	15.2	N.G.			
15	33.0	51.2		29.2	39.4		21.9	15.5				
16	31.7	49.2		26.3	29.4		23.5	21.0				
17	32.9	50.0		28.8	37.2		22.9	19.0				
18	30.2	38.6		28.7	36.8		22.2	16.3	N.G.			
19	31.4	43.0		29.4	38.4		23.4	19.4				
20	32.1	44.5		28.9	37.0		22.7	16.6	N.G.			
21	34.2	58.8		28.2	31.2	N.G.	21.0	17.0	N.G.			
22	32.2	48.6		28.1	33.2		23.9	17.4	N.G.			
23	30.2	39.8		29.3	37.8		24.4	19.6				
24	31.8	36.8		27.7	29.0		24.9	23.0				
25				30.2	41.0		24.8	22.0				
26				29.3	35.0		23.9	19.4				
27				28.3	35.8		24.1	20.0				
28				29.2	40.0		23.5	18.0				
29				28.2	38.0		24.6	21.0				
30				26.7	24.0		24.1	19.0				
31							23.1	21.6				
32							21.2	14.0				
33							23.0	20.6				
34							21.4	13.5				
35							23.4	17.5				
36							22.8	18.0				
37							22.7	16.4				
38							22.7	17.2				
39							20.8	13.0				
40							22.3	20.4				
41							23.8	22.0				
42							23.4	18.0				
43							23.3	16.8				
44							23.7	19.6				
45							24.5	22.0				
46							24.6	21.6				
Ave.	32.1	48.6		28.1	33.0		[illegible]	18.6				
S.D.	[illegible]	6.6		1.5	8.5		[illegible]	[illegible]				

TABLE A.9

RESIDUAL PROPERTIES OF KAPTON FILM AFTER STRESSED-HUMIDITY EXPOSURES AT 85°C

Specimen No.	200 Hr. Exposure			400 Hr. Exposure								
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	30.2	36.8		26.6	16.0							
2	27.5	23.8		25.6	16.0	N.G.						
3	28.2	27.4		27.0	22.0							
4	32.2	46.6		27.5	22.0							
5	28.2	30.8		25.4	15.6							
6	30.2	34.6		29.1	28.0							
7	28.0	27.6		27.0	20.0							
8	29.3	32.0		28.5	24.0							
9	28.2	24.6	N.G.	27.2	23.0							
10	29.2	32.8		27.6	27.0							
11	28.8	28.4		28.0	23.6							
12	29.8	31.4		26.0	16.0	N.G.						
13	30.7	35.8		26.5	19.0							
14	30.3	37.0		23.6	10.0							
15	30.1	35.6										
16	24.4	27.7										
17	22.1	9.0	N.G.									
18	27.1	20.4										
19	29.5	31.4										
20	31.2	41.2										
21	29.3	32.2										
22	20.5	7.4										
23	29.5	33.4										
Avg.	28.7	31.0		27.0	20.9							
S.D.	2.6	8.1		1.4	5.1							

TABLE A.10

RESIDUAL PROPERTIES OF KAPTON FILM AFTER STRESSED-HUMIDITY EXPOSURES AT 75°C

Specimen No.	300 Hr. Exposure Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	600 Hr. Exposure Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	22.3	33.0		28.9	27.8							
2	30.8	42.0		26.8	18.0							
3	20.1	7.0	N.G.	28.6	31.6							
4	28.2	28.0		28.5	30.4							
5	30.3	37.0		29.0	31.0							
6	30.5	50.0		30.7	39.0							
7	28.2	25.0	N.G.	27.8	24.5							
8	32.2	42.0		28.2	31.0							
9	29.5	35.0		27.4	23.0							
10	30.6	35.0		30.1	34.0							
11	29.5	18.0		16.0	4.0							
12	29.3	29.0		27.7	22.0							
13	29.5	32.0		29.5	28.2							
14	29.0	34.0										
15	30.4	35.0										
16	27.4	24.0										
17	28.5	29.0										
18	25.7	17.0	N.G.									
19	30.0	32.0										
20	29.0	33.0										
21	28.3	24.0										
22	30.0	34.0										
23	29.5	31.0										
24	32.0	44.0										
25	30.6	37.0										
26	28.7	29.0										
27	30.5	37.0										
28	29.5	31.0										
29	27.5	44.0										
30	28.7	26.0										
31	31.5	42.0										
32	30.5	37.0										
33	27.0	19.0										
34	29.0	29.0										
35	29.3	26.0										
Avg.	29.6	32.9		27.6	26.5							
S.D.	1.1	7.0		3.7	8.7							

TABLE A.11

PROPERTIES OF UNAGED KAPTON FILM AS DETERMINED BY DUPONT

Specimen No.	Roll A - Location 1(1)			Roll A - Location 2(2)			Roll A - Location 3(3)			Roll B		
	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result	Tensile Strength (10^3psi)	Ult. Elong. (%)	Test Result
1	35.2	72.0		32.0	60.0		34.8	69.0		30.8	46.0	
2	35.6	75.0		32.3	63.0		35.9	75.0		36.8	70.0	
3	32.0	54.0		32.5	61.0		36.0	75.0		34.7	62.0	
4	35.9	75.0		32.8	67.0		32.8	58.0		34.2	60.0	
5	35.0	68.0		34.8	74.0		36.8	80.0		37.7	75.0	
6	32.9	62.0		33.4	67.0		34.9	72.0		36.1	68.0	
7	35.7	75.0		36.0	83.0		33.6	65.0		35.8	68.0	
8	32.3	57.0		33.2	66.0		36.3	80.0		30.1	40.0	
9	30.9	50.0		34.8	77.0		36.7	78.0		34.3	57.0	
10	36.4	79.0		34.6	77.0		37.7	85.0		37.2	72.0	
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												
32												
Avg.	34.2	66.7		33.6	69.5		35.6	73.7		34.8	61.8	
Std. Dev.	0.24	10.2		0.23	7.8		0.25	8.0		0.24	11.4	

(1) Top of roll.
(2) 100 ft. further into roll.
(3) 200 ft. further into roll.
(4) Each roll represents an adjacent slit lane (from Mill Roll 07792) to those from which the data in Table A.1 was obtained.

☆U.S.Government Printing Office: 1984 759-062/689